Chapter 1: Introduction to LCIA and LCM in the South African context

This chapter provides a general overview (from a South African perspective) of the sustainable development concept, as well as Environmental Management System (EMS) tools that have been introduced to enhance sustainability performances in industry. In particular, the Life Cycle Management (LCM) approach is presented, together with the Life Cycle Impact Assessment (LCIA) phase of LCM, through which the environmental impacts of life cycle systems in industry are evaluated. The chapter emphasises the specific South African environmental conditions that must be addressed by the LCIA phase.

1.1 Sustainable development in the South African context

The first major concerns about the sustainability of development were published in the early 1960s [1, 2]. These suggested a link between development and human activities and damage to biological species and human health. In the same decade, concerns about a global population explosion and its impacts on the environment and social structures were raised [3]. By the early 1970s, these were translated into a call for the integration of environmental and development strategies. This approach was emphasised at the United Nations Conference on the Human Environment in 1972, which stated that [4]:

"*Although states have a right to exploit their own resources pursuant to their own environmental policies, they nevertheless have a responsibility to ensure that activities within their borders do not cause damage to the environment of other states or areas beyond their limits of national jurisdiction*".

The end of the 1970s saw the move to link environment and economic aspects, with the International Conference on Environment and Economics, held in 1984, concluding that the environment and economics should be mutually reinforcing [5]. Debates and work in this field continued throughout the 1980s, when the United Nations World Commission on Environment and Development (WCED) finally coined the concept of sustainable development in the now famous Brundtland report of 1987 [6]:

"*Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs*".

The exact definition of sustainable development is still disputed, as are the underlying aspects thereof, but in general it is agreed that the interactions of the three pillars: economic, social and environmental, as are shown in Figure 1.1, collectively contribute to sustainable development [7]. Thus, meeting the needs of the future depends on how well these interconnected economic, social, and environmental objectives, or needs, are balanced during current decision-making processes [8].

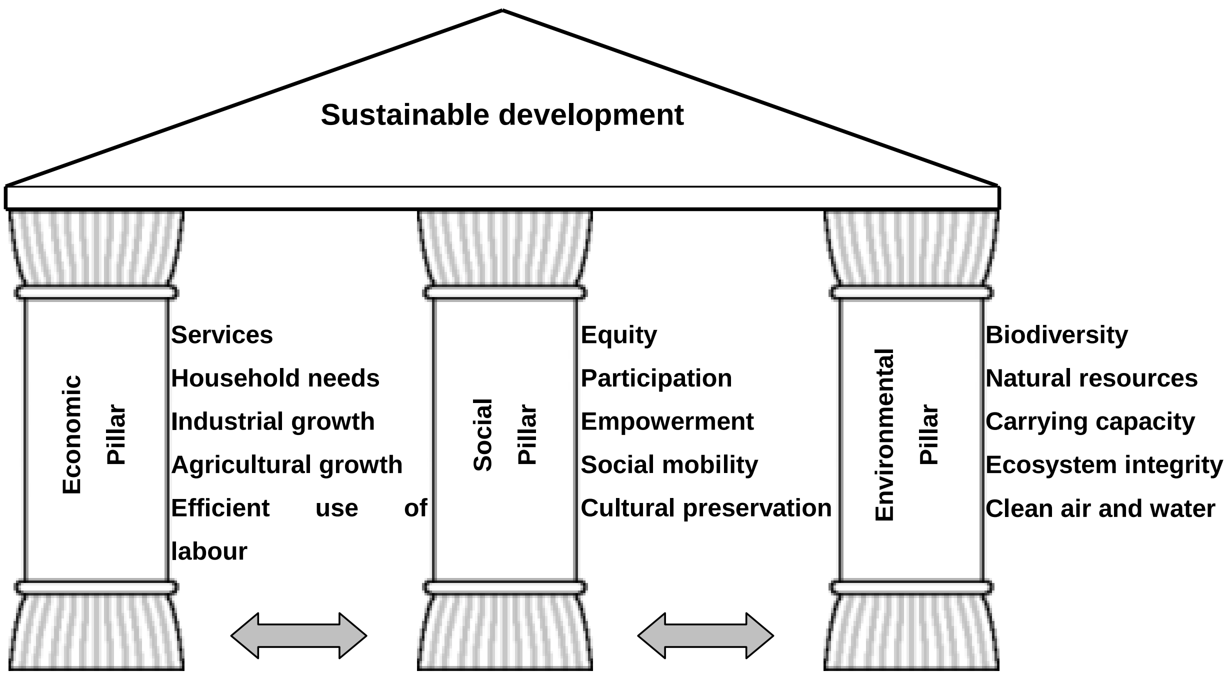

Figure 1.1: The three pillars (and interactions) of sustainable development

South Africa has a unique mixture of characteristics relating to the objective of balancing these three pillars (in an interconnected manner). Observations regarding the exceptional complexity of sustainable development in the South African context have been reported since the beginning of the 1990s [9]:

"*South Africa with its mix of First World environmental problems such as acid rain, and Third World environmental problems such as soil erosion, is a microcosm of the environmental challenges facing the planet*".

1.1.1 The economic pillar of sustainability in the South African context

The South African economy has traditionally been based on agricultural and mining-related industries. During the 1960s, these two primary sectors accounted for 25% of South Africa's Gross Domestic Product (GDP). However, as is shown in Table 1.1, their importance reduced to less than 10% of the national GDP by the turn of the century [10].

Table 1.1: Contribution of industry sectors to the South African GDP [11]

Industry sector	Percentage (%)				
	1960	1970	1980	1990	2000
Agriculture, forestry and fishing	12.4	7.9	6.8	4.6	4.1
Mining and quarrying	12.7	9.0	21.1	8.7	5.4
Manufacturing	21.0	23.9	22.5	23.5	26.8
Electricity and water	2.5	2.6	3.1	4.0	3.2
Construction	3.1	4.2	3.3	3.2	2.7
Tertiary sector, including transport, finances, etc.	48.3	52.4	43.2	56.0	57.8

Since 1990, the South African economy has been significantly transformed in terms of the growth of the manufacturing sector. Prior to the 1990s this sector was dominated by heavy industries relating to petroleum, chemical and metallurgical products [10]. Although this sector as a whole contributed 27% to the total GDP in 2000, less than 4% of the total GDP was attributable to the chemicals manufacturing industry [10]. The metallurgical industry still plays an important role, but the export of value-added products has increased significantly since the 1994 democratic elections. This can, in part, be ascribed to the South African government's 1996 Growth, Employment and Redistribution (GEAR) strategy [12]. The new industrial policy strives to achieve a balance between greater openness and improvement in local competitiveness, while pursuing a process of industrial restructuring aimed at expanding employment opportunities and productive capacity, specifically to open the domestic economy to international competition.

The focus of industry on export products is further intensified through the local consumer markets, which are small in relation to world markets. Although the population is estimated at roughly 45 million [13], poverty levels remain high as only 40% of the population contributes to the economy of the country and less than 12% of the possible economically active group earns more than R 2500 (approximately US$ 300) per month [13].

The automotive sector is a good example of an export-focused industry, which has seen the introduction of the Motor Industry Development Programme (MIDP) by the national Department of Trade and Industry [14]. Since the start of the initiative in 1995, a 37% increase in the average annual export rate has been achieved, with export of passenger vehicles increasing by approximately 185% since 1998. The total sales from exported passenger vehicles was projected to increase by more than 10% in 2002 from 2001, in contrast to a projected decrease of 6% in local sales [15].

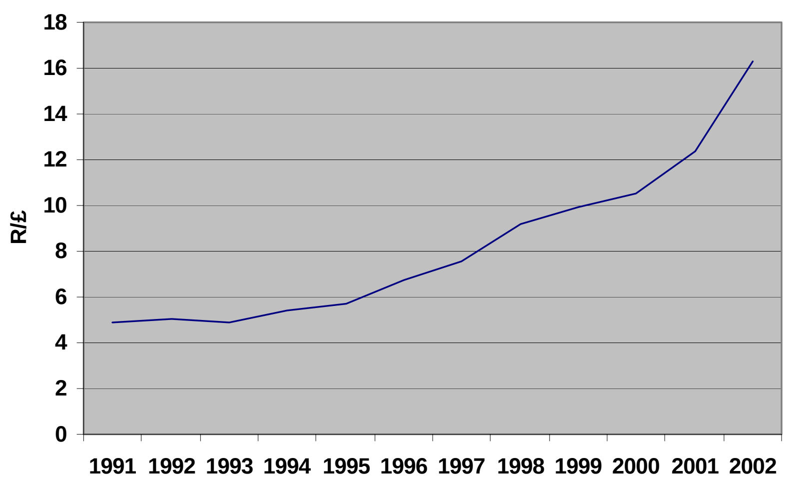

Figure 1.2: Exchange rate of the South African Rand against the British Pound [16]

As a whole, economic growth has recovered, capital inflows resumed and business and consumer confidence increased, resulting in a real GDP increase of between 2 and 4% since 1993 compared to an average of 1% per annum from 1983 to 1993 [16]. However, a dramatic decrease in the value of the South African currency (Rand) has occurred in the past (Figure 1.2 - 30% in the year preceding the first quarter of 2002), although the currency has recovered to some extent (in the year preceding the first quarter of 2003) [16]. A decreased value of the currency could be positive for export purposes due to lower and competitive international production costs, but could impact negatively on the local poverty reduction goals of the South African government [17], i.e. the social sustainability of the South African society.

1.1.2 The social pillar of sustainability in the South African context

Less than 5% of South Africans are estimated to enjoy conditions similar to those of developed countries [13], whereas the majority of South Africans are subject to developing country conditions, i.e. rural and spontaneous urbanisation. Of the estimated nine million South African households in 1996, approximately 50% had access to formal energy supply as electricity for cooking, heating and lighting as shown in Table 1.2 [18].

Table 1.2: Energy sources for cooking, heating and lighting in SA households [18]

Energy source	Cooking	Heating	Lighting
Electricity directly from authority	4 246 688	4 010 283	5 188 644
Electricity from other sources, i.e. local generation	18 617	20 567	32 182
Gas	286 657	107 689	35 512
Paraffin	1 943 862	1 294 964	1 144 014
Wood	2 073 219	2 417 724	-
Coal	320 830	735 632	-
Animal dung	106 068	84 447	-
Unspecified/Other	63 629	388 266	2 659 221[a]
Total	**9 059 571**	**9 059 571**	**9 059 571**

a 97% candle use

Of the nine million households, 45% had direct supply of water inside their dwellings and roughly 50% of the households had access to latrines and waste removal services. More than 12% of the households do not use either flush or chemical toilets, or latrines consisting of pits or buckets. The transformation initiatives of the national government have resulted in approximately one million homes being built since the 1994 democratic elections [19]. However, access to these basic services remains on the development agenda [17].

The population growth rate is estimated to be between 2 and 3% per year [18]. However, it has been estimated [20] that the HIV/AIDS pandemic caused 25% of all South African mortalities in 2000 and its impact on the future growth rates is uncertain. Of significance is the increased movement of the population from rural to urban areas, as shown in Figure 1.3 [21].

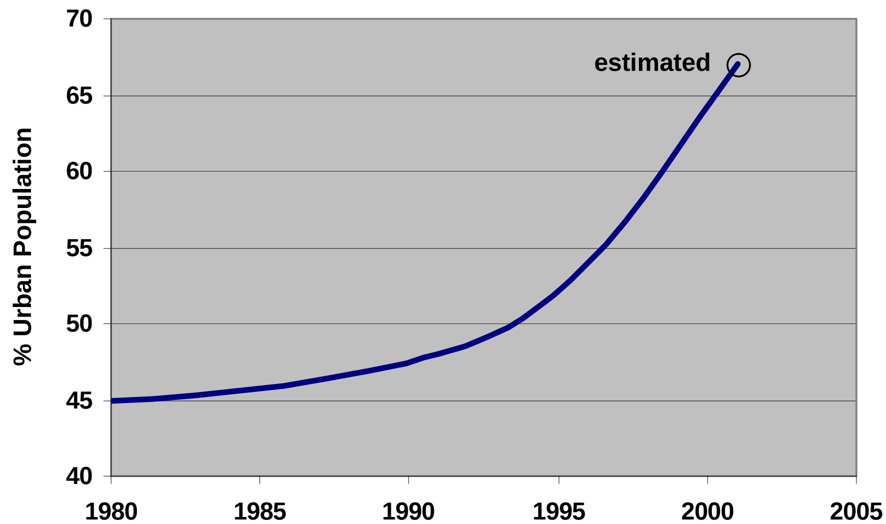

Figure 1.3: Increased movement from rural to urban areas in South Africa [21]

The increased movement from rural to urban areas results in uncontrolled development in urban areas, with consequent energy, water, waste and sanitation problems together with diseases, including HIV, which the national government must deal with. The government has also taken steps to mitigate additional health-related issues in South African urban areas, such as the low smoke fuels project, which intends to address respiratory problems due to smoke inhalation in underdeveloped communities [22].

The underprivileged South Africans that live in rural areas typically lack resources and technologies and do not have access to the infrastructure that provides economic opportunities and preserves human and environmental health [23]. The urgent short-term needs prompt cultivation of marginal lands, the depletion of water resources, and the overexploitation of trees and other plants for firewood, medicinal herbs and food. The consequence is the local over-exploitation and mismanagement of valuable soil and water resources [24].

In terms of education, the management of the specific South African social problems and their interactions with the economic and environmental pillars of sustainable development is summarised by the United Nations economic and social development programme [25]:

"*The most important capacity requirement is to instil realism in the determination of development policies and strategic orientation and their time frame for implementation. Capability to identify the problem areas on the basis of a scientific situation analysis, and the capability to choose the best alternative to address the concerns, are also very important*".

1.1.3 The environmental pillar of sustainability in the South African context

South Africa is ranked as the third most biologically diverse country in the world, which is mainly due to its varied vegetation types [26]. The high level of diversity is attributable to the range of climatic, geological, soil and landscape forms that are found in South Africa [23]. South Africa is divided into 22 primary water catchments or drainage regions [27], which are grouped into 18 eco-regions consisting of specific vegetation types [28]. The catchments and eco-regions of South Africa are shown in Figure 1.4 [23].

The United Nations Conference for Environment and Development in Rio de Janeiro in 1992 stipulated that 10% of each vegetation type must be conserved for pristine or near pristine use. However, South Africa currently formally conserves only 6% of the whole country and several vegetation types are under-represented [29, 30, 31].

	Water catchments
A	Limpopo, Groot Marico, Crocodile, Matlabas, Palala, Mogalakwena, Sand, Nzhelele, Luvuvhu
B	Olifants, Shingwedzi Letaba, Olifants, Wilge, Elands, Steelpoort, Selati, Ohrigstad, Blyde
C	Vaal, Wilge, Liebenbergs, Klip, Suikerboschrand, Mooi, Rhenoster, Vals, Vet, Harts, Modder
D	Orange River basin, Caledon, Kraai, Senqu, Seekoei, Brak, Hartebeest, Sak, Sout
E	Olifants River (Cape) basin, Doring, Sout, Kromme, Hantams, Tanqua
F	Buffels River basin, Groen, Swartlintjies
G	Berg River basin, Great Berg, Salt
H	Breede River basin
J	Gouritz River basin, Touws, Groot, Buffels, Dwyka, Gamka, Leeuw, Olifants, Kammanassie
K	Krom, Keurbooms
L	Gamtoos, Gouga, Groot, Kariega, Buffalo, Salt
M	Swartkops River basin
N	Sundays River basin,Vogel, De Hoop
P	Bushmans River basin
Q	Fish River basin, Great & Little Fish, Kat, Konap, Vlekpoort, Great Brak
R	Buffalo River basin, Keiskamma, Nahoon
S	Kei River basin, Black Kei, White Kei, Tsomo, Little Kei
T	Mzimvubu, Bashee, Mtata, Tsitsa, Tina, Kaneka, Mzimtlana, Mtamvuma, Mzimkhulu
U	Mgeni, Mvoti & Mkomazi river basins
V	Tugela River basin, Mooi, Bloed, Buffalo, Sundays
W	Mfolozi, Pongola, Mkuze, Usutu, Mhlatuze, Mfolozi, Ngwavuma, Assegai, Mkonda, Mpuluzi
X	Komati, Crocodile & Sabie River basins, Lomati, Kaap, Elands, Sand

Eco-regions
Bushveld Basin
Cape Folded Mountains
Central Highlands
Eastern Coastal Belt
Eastern Uplands
Great Kaap Plateau
Great Escarpment Mountains
Great Karoo
Highveld
Lebombo uplands
Limpopo plains
Lowveld
Nama Karoo
Namaqua Highlands
Natal Coastal Plains
Southern Coastal Belt
Southern Kalahari
Western Coastal Belt

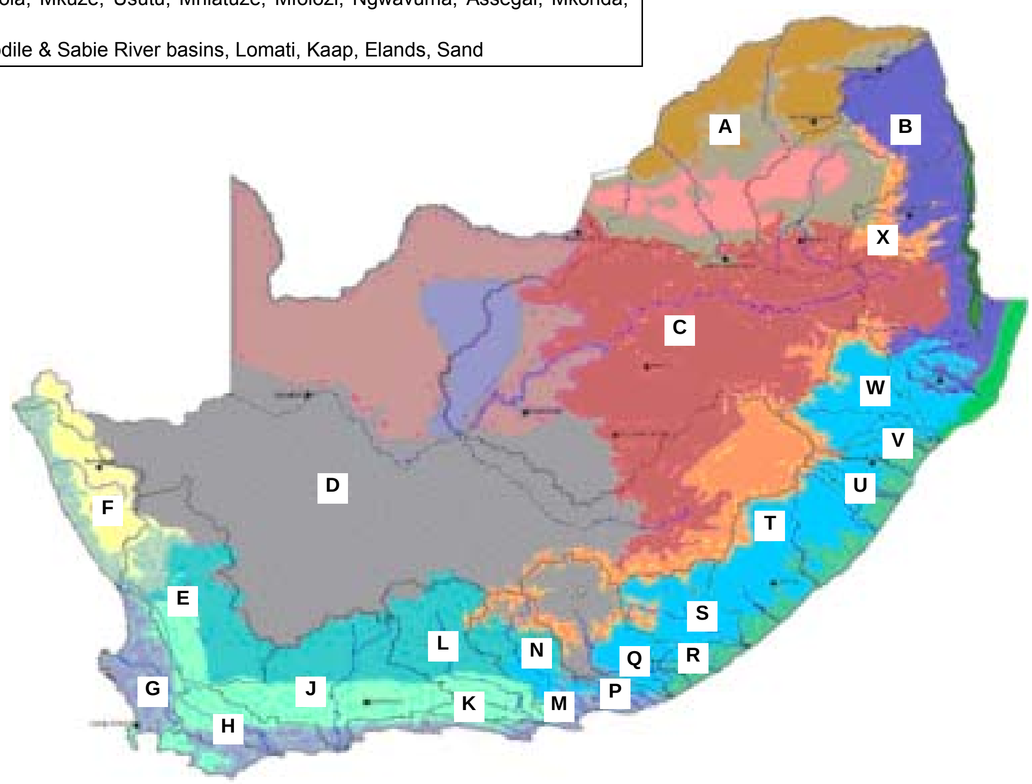

Figure 1.4: Primary water catchments and eco-regions of South Africa [23]

South Africa lacks important arterial rivers or lakes and extensive water conservation and control measures are required. Table 1.3 indicates the projected increase in demand on the national freshwater supplies [23]. With an estimated maximum freshwater yield of 33 290 million cubic metres per year, the growth in water usage threatens to outpace supply [27]. South Africa has an average rainfall of 497 mm/year [32] (compared to the world average of 860 mm) and is subject to prolonged droughts. Pronounced variations in the annual rainfall, especially in arid parts, cause sporadic wet and dry periods [27]. These, together with land mismanagement, have led to a dramatic increase in the loss of topsoil (35%), an important agricultural resource [33]. Other important issues, which are dealt with in newly introduced legislation [10], include pollution of rivers from agricultural runoff and discharge from informal urban settlements.

Table 1.3: Projected increase in water demand from different sectors in SA [23]

Sector	1996 (million cubic metres per year)	2030 (million cubic metres per year)	Percentage increase
Urban and domestic	2 171	6 936	219.5
Mining and industrial	1 598	3 380	111.5
Irrigation and forestation	12 344	15 874	28.6
Environmental (nature)	3 932	4 225	7.5
Total	**20 045**	**30 415**	**51.7**

South Africa produces an estimated 460 million tonnes of waste, of which industrial and mining waste amounts to approximately 419 million tonnes per year (81%) [34]. Waste generation in urban areas is highly variable and depends on the socio-economic level of the community. In 1991, an estimated 1200 municipal landfill sites disposed 95% of the urban waste. However, only 18% of these sites were under permit, which became a legal requirement in the same year. Long-term planning, information, appropriate legislation and capacity to manage the waste streams have historically been lacking [35]. This is especially true for waste generated in rural areas, and specifically waste generated by health care facilities.

These issues are addressed to some extent through the new national waste management strategy, an initiative of the national Department of Environmental Affairs and Tourism [23].

The unique (social and economic) conditions in South Africa therefore result in a number of environmental pressures, some of which are shown in Table 1.4 [23]. Incorporation of sound environmental management practices in industry is therefore essential to relieve the pressures and to ensure sustainable development.

Table 1.4: Environmental pressures and expected future trends in South Africa [23]

Driving force	Resulting pressure	Expected future trend
Economic growth and export	Increased demand for resources; conversion of natural habitats; generation of pollution and waste; introduction of alien species	Pressure will increase unless production methods are changed, and understanding of impacts improves
Population factors (growth, mobility, distribution and structure)	Increased demand on resources; rabid urbanisation; increased and concentrated generation of pollution and waste; smaller proportion of the population contributing to form economic activities	Pressure will increase severely
National priorities: provision of basic needs for all South Africans	Increased demand on resources; resettlement of people in marginal areas due to land reform	Pressure will remain constant or increase slightly
Macro-economic and sectoral policies	Unsustainable use of resources; population segregation, inequality and widespread poverty	Pressure could stabilise or reduce, if new policies are implemented and enforced
Gaps in understanding	Unsustainable resource use practices; uncontrolled degradation of ecosystem functioning	Pressure will remain constant unless the 'precautionary principle' is applied
International agreements	Strategies for sustainable resource use; reduction of pollution	Pressure is likely to remain constant
International standards	Implementation of sustainable production methods, which reduce impacts	Increase slightly as environmental awareness increases

1.2 ISO 14000 as a decision support mechanism for sustainable development

The trend towards globalisation and increased competition has identified the need to incorporate Environmental Management Systems (EMSs) into existing business practices [36]. The increased pressure experienced by companies to demonstrate improved environmental stewardship and the associated burden of the related accountability, resulted in the need for an international EMS standard. The consequence was the development and publication of the ISO 14000 family of standards within a period two years by the International Organization for Standardization (ISO) [37]. ISO 14000 aims to achieve standardisation in the field of environmental management and thereby guide the implementation and maintenance of an EMS.

The responsibility to develop and continually improve the ISO 14000 standard lies with the Technical Committee 207 (TC 207) of ISO [38], which was established in 1993. As is shown in Figure 1.5 [37], TC207 has distinguished two main focus areas for environmental tools and related standards:

- Organisation evaluation, including EMS, Environmental Performance Evaluation, and Environmental Auditing, and
- Product or process evaluation, including Life Cycle Assessment (LCA), Environmental Aspects in Product, and Environmental Labelling.

Within the corporate context, the International Institute for Sustainable Development (IISD) has redefined sustainable development to focus the attention of the concept on areas of specific interest and concern for business enterprises [39]:

"*For the business enterprise, sustainable development means adopting business strategies and activities that meet the needs of the business and its stakeholders today while protecting, sustaining and enhancing the human and natural resources that will be needed in the future*".

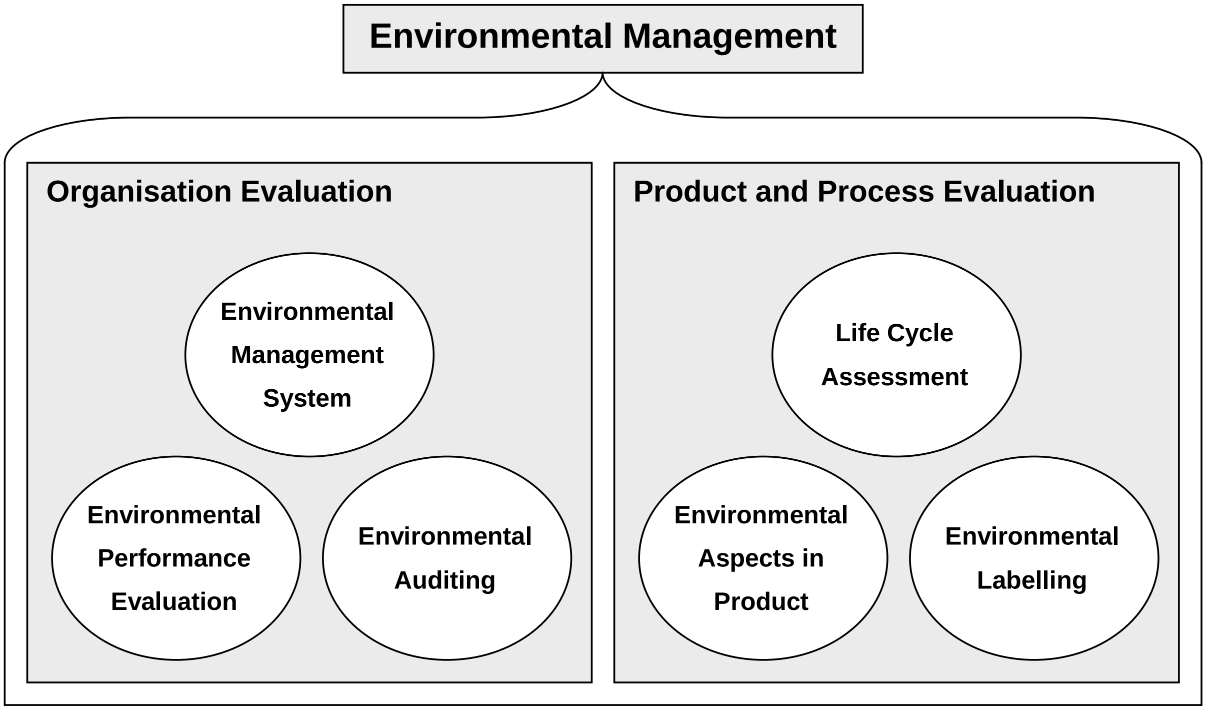

Figure 1.5: Focus areas of TC207 environmental tools and standards [37]

ISO 14000 contributes to sustainable development in the extent that it assists organisations meeting the objectives of this definition [40]. However, as is shown in Figure 1.6 [41], the often complex EMS and practices that are incorporated in an organisation's existing structure through the ISO 14000 standards deals with environmental management solely. Human, or social, and economic aspects do not receive much attention in the standards' documentation. Organisations need to address these aspects through other management systems to ensure that all objectives of sustainable development are met.

The TC207 technical committee of the South African Bureau of Standards (SABS) has accepted some of the standardisation documents of ISO as standard codes of practice [42]. Acceptance of the ISO 14000 series indicates that LCA can be used as a valuable tool for environmental management decision purposes (Figure 1.5), not only in developed countries, but also in developing countries such as South Africa.

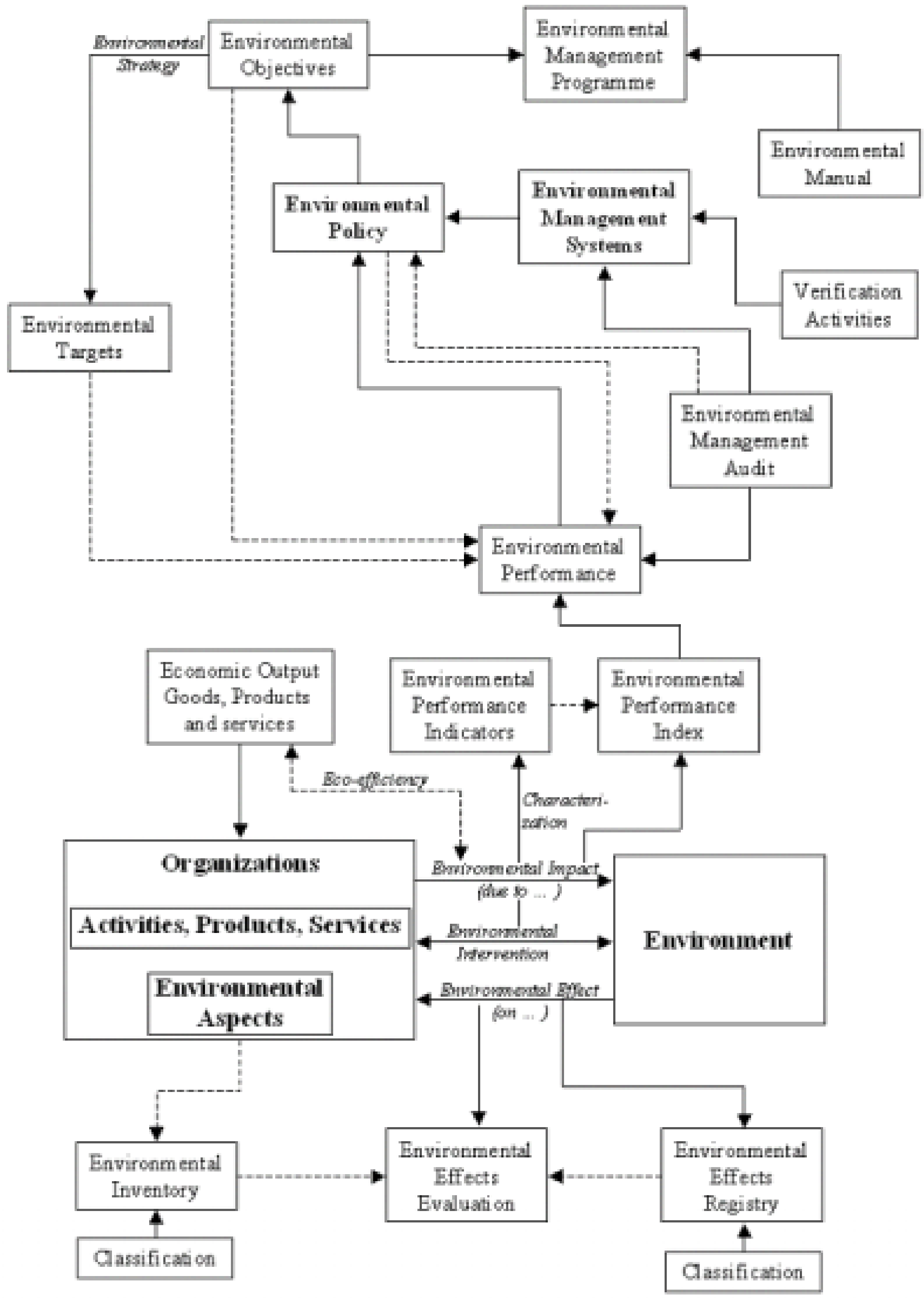

Figure 1.6: Framework for a typical environmental management system [41]

1.3 Life Cycle Assessment (LCA) and decision-making

The primary custodian of technical developments in the field of LCA (as a tool in the ISO 14000 series) is the Society of Environmental Toxicology and Chemistry (SETAC) [43]. A number of workshops sponsored by SETAC documented LCA as a quantitative procedure to assess environmental burdens associated with the life cycle of an activity (product, process, or service) by [44]:

- Identifying and quantifying energy and materials used and wastes released to the environment.
- Assessing the potential impact of those energy and material uses and releases to the environment.
- Identifying and evaluating opportunities to affect environmental improvements.

The LCA tool is, however, criticised in that subjective results may be obtained for the routine analyses of products due to [43]:

- The subjective basis and limitations in the collection and analyses of data.
- Variations in the temporal scale, spatial scale and locale, and assignment procedures of values to different environmental impacts.

These deficiencies must be considered when the LCA procedure is applied. A complete life cycle includes raw material extraction (including water), processing, transportation, manufacturing, distribution, use, re-use, maintenance, recycling, and final waste disposal [45]. The main objectives of executing a LCA study are to [46]:

- provide a profile (as complete as possible) of the interactions of an activity (product, process or service) with the environment;
- contribute to the understanding of the overall and independent nature of the environmental consequences of human activities; and
- provide decision-makers with information, which quantifies the potential environmental impacts of activities and identifies opportunities for environmental improvements.

In this respect, companies have used LCAs to fully comprehend the overall environmental consequences of products and changes in production processes [47, 48, 49].

This, in turn, has introduced the concept of product stewardship as a business decision mechanism [50], whereby responsibility is accepted for the environmental practices upstream (suppliers) and downstream (customers or clients) of a company's activity, i.e. the "cradle-to-grave" concept.

LCA is also increasingly used as a tool for policy development by regulatory authorities that influence business decisions [46, 51]. Options for possible waste management practices have been good examples of using LCA results for policy purposes [52]. As LCA results are often used for company in-house and policy decisions, the formal ISO LCA procedure supports the main phases of theoretical decision-making and analytical processes [53]:

- Structuring of the problem.
- Construction of the decision/preference model.
- Sensitivity analysis.

1.3.1 The Life Cycle Assessment (LCA) procedure

The framework for executing an LCA study is well documented in the ISO publications and is illustrated in Figure 1.7 [54]. In general, a complete LCA study must consist of four phases [55]:

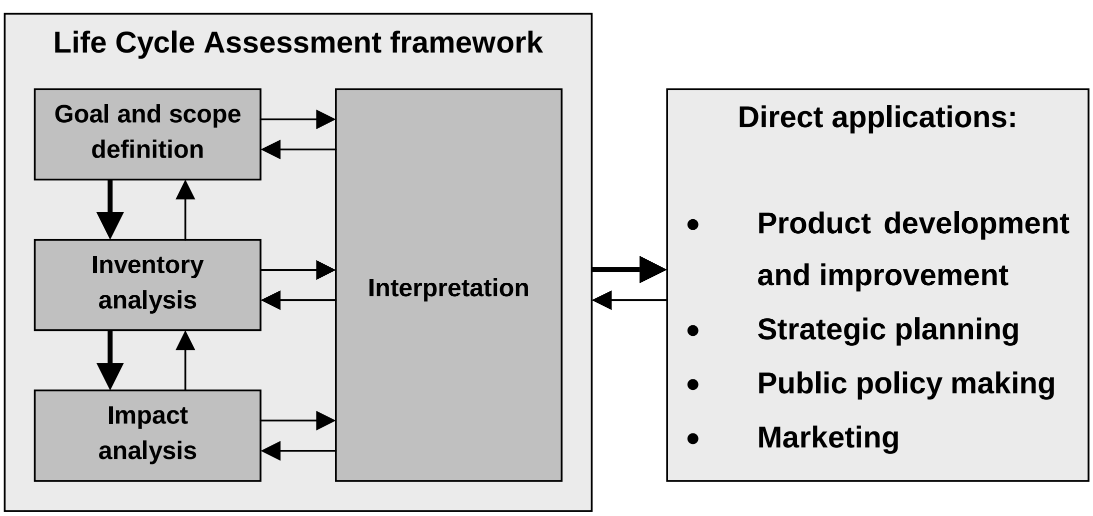

Figure 1.7: Standardised phases of the LCA [54]

- Goal and scope definition, which describes the application or specific interest and indicates the target group. A detailed description of the system to be studied is included, providing a clear delimitation of scope, periods and system boundaries.
- Inventory analysis, which quantifies the environmentally relevant inputs and outputs of the studied system. The ISO/TC207 technical group has provided a framework for the inventory analysis. This is shown in Figure 1.8 [56].
- Impact assessment, which quantifies the environmental impact potential of the inventory data and, in turn, is divided into [45]:
    - classification, whereby inventory data is categorised into impact categories;
    - characterisation, which determines the contribution of the inventory data to each impact category, quantitatively or qualitatively; and
    - valuation, whereby the different impacts are normalised and weighed against each other.
- Interpretation and improvement analysis, whereby options are identified and analysed to reduce the environmental impacts of the studied system.

1.4 Life Cycle Assessment (LCA) and Life Cycle Management (LCM)

The Design for Environment (DfE) concept has resulted in certain modifications that have been made to the environmental LCA procedure to adapt to DfE applications [57]. The consequent Life Cycle Engineering (LCE) approach [58] evaluates the environmental implications of a product, process or service in the design phase, i.e. proactively rather than reactively as is the case with many assessment tools. LCE further incorporates data of economic and environmental aspects, together with an evaluation of the designed technology, as a combined decision support system in the design phase (see Figure 1.9 [59]). Economic aspects are assessed through the Total Cost Assessment (TCA) and Life Cycle Costing (LCC) tools [60] and environmental aspects through the conventional LCA tool and related Life Cycle Impact Assessment (LCIA) procedure [61]. The comprehensive integration of economic and environmental impact assessments for typical life cycle evaluations of products (as it has been applied in the South African industry [62]) is illustrated in Figure 1.10.

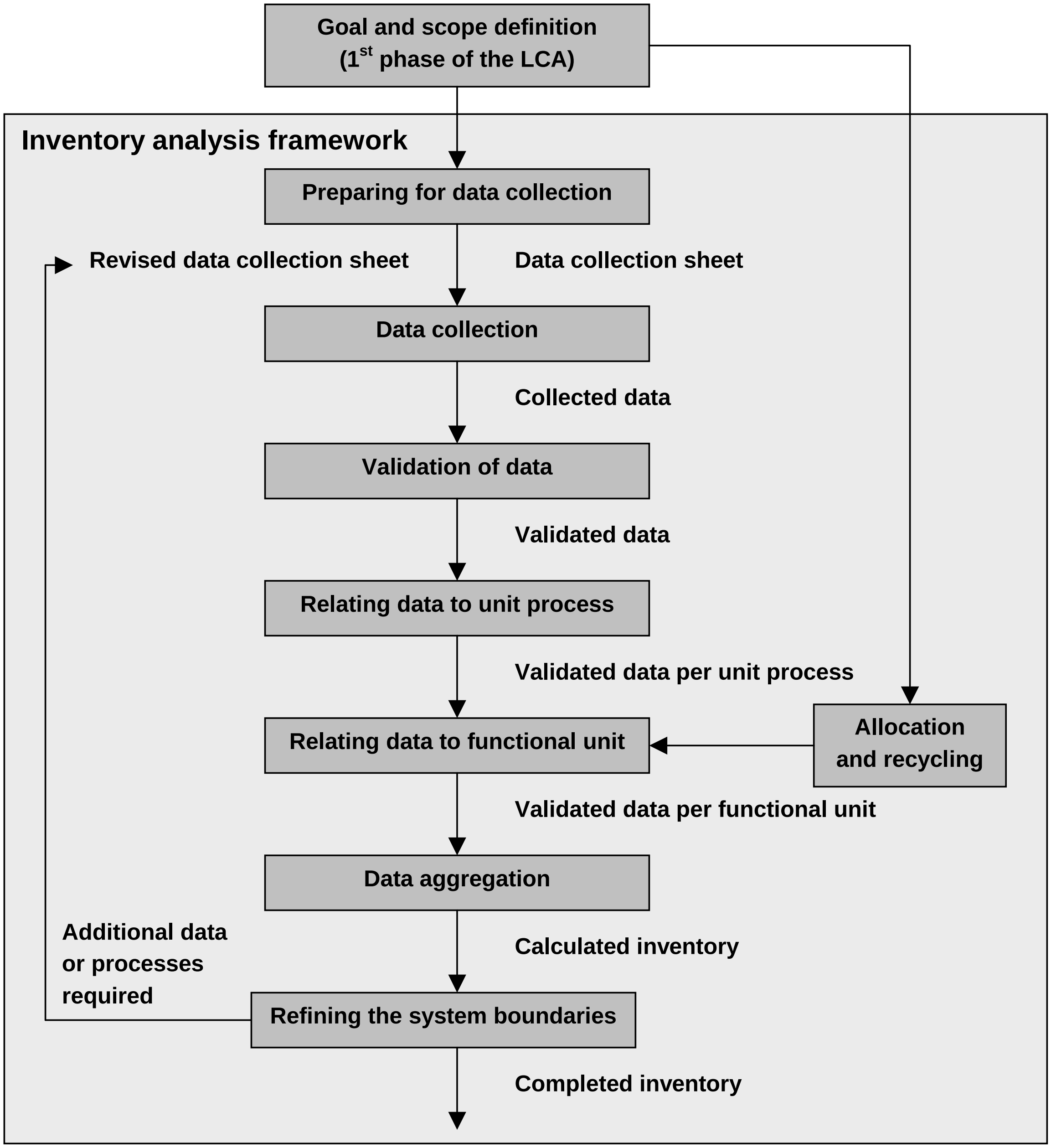

Figure 1.8: Procedure for the inventory analysis phase of a LCA study [56]

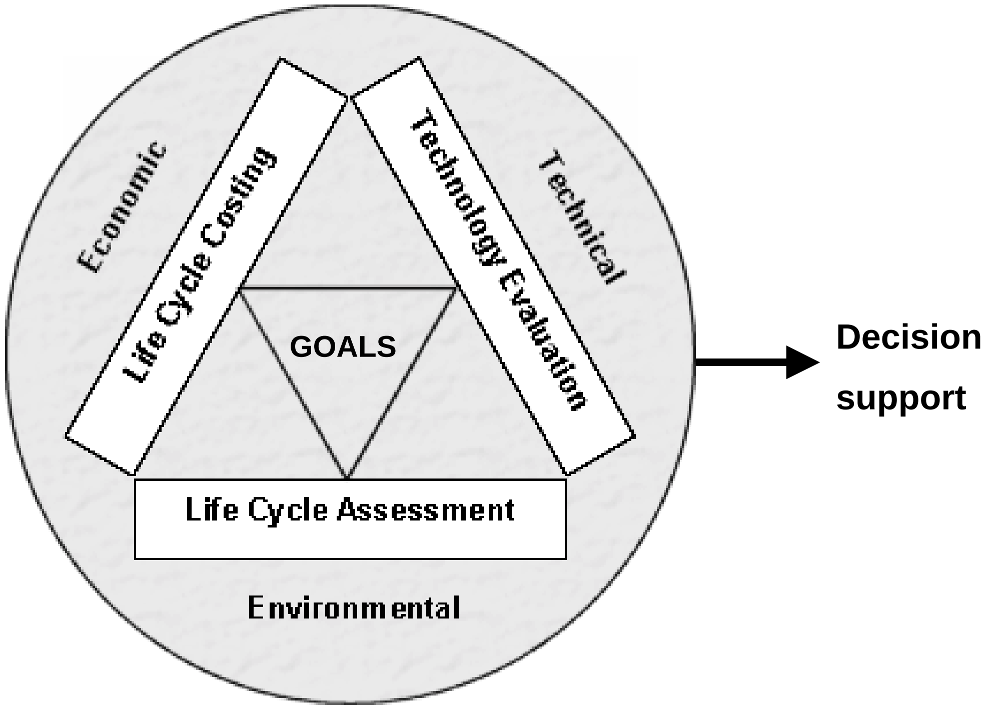

Figure 1.9: The decision support mechanism of Life Cycle Engineering [59]

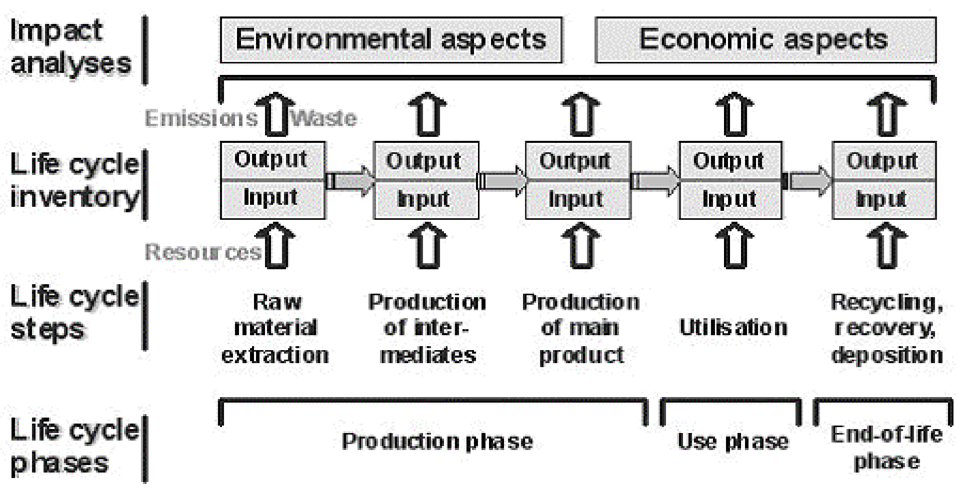

Figure 1.10: The life cycle approach for "cradle-to-grave" analyses [62]

Life Cycle Management (LCM) is an extension of the LCE concept, i.e. the life cycles of products, processes and services are managed beyond the design phase. Thereby, the total economic, environmental and social performances of business activities are evaluated, e.g. the cost of potential liabilities to a manufacturer [63]. These performances objectives manifest in three operational focal points that are fundamental to the manufacturing sector (as defined by the Standard Industry Classification [64]), including all economic activities within the manufacturing value chain, e.g. agriculture, mining, etc.:

- Projects, which drive change in internal operational practices. The concept of sustainable development must be integrated into the planning and management of the life cycle of projects.
- Assets, which are required in the manufacturing process. The life cycle of assets must be optimised in terms of sustainable development performances objectives of the manufacturing facility.
- Products, which determine the economic value of manufacturing operations. The influence of products (including materials and services) on economies, environments and society as a whole must be considered, i.e. the concept of product stewardship [50].

A comprehensive LCM approach is subsequently required, which assures that the operational processes are consistent and that there is effective sharing and coordination of resources, information and technologies [65]. Such a holistic LCM approach requires an affective integration of the three life cycles (projects, assets and products) within a manufacturing organisation, as is shown in Figure 1.11 [66].

1.4.1 Project Life Cycle Management

Project LCM typically applies a staged framework approach, whereby a project's performance and key deliverables are reviewed at the end of each life cycle stage [67]. These gate-reviews serve as decision points to determine if the continuation of the project should be supported. Sustainable development can only be adequately incorporated in the appraisal process if it is evident at the gate-review meetings as [68]:

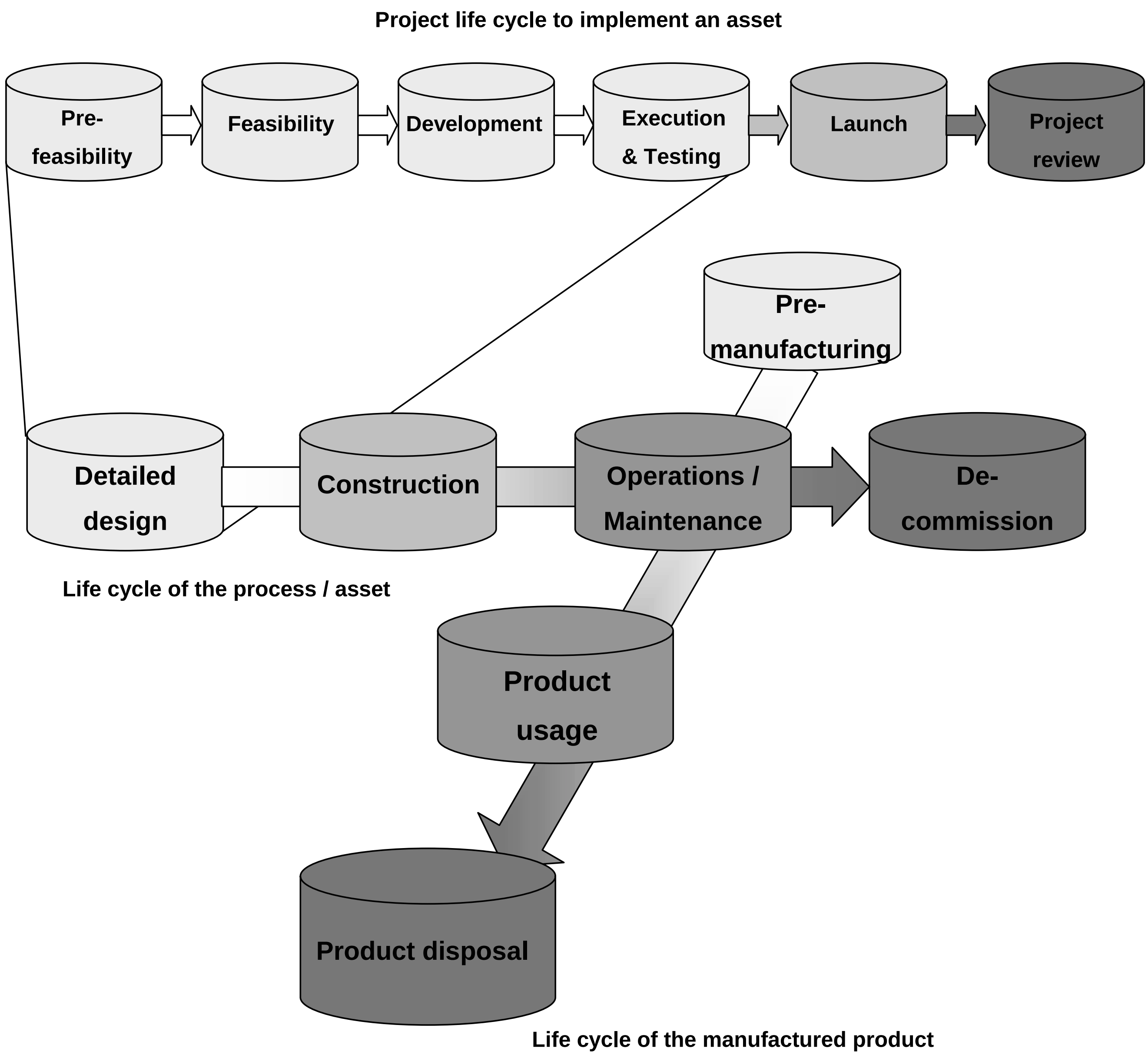

Figure 1.11: Integration of typical project, asset and product life cycles [66]

- Separate information presented to the decision gate meeting, also referred to as decision documentation, which include the status of project deliverables, project plan, technological feasibility, financial feasibility, etc.
- Typical criteria addressed by the meeting, i.e. sustainable development criteria of the project must be addressed in parallel with other aspects, e.g.

technological feasibility, financial feasibility, etc. in order to ensure that it receives due consideration.

At present the environmental and social performance objectives of sustainability are ill represented in project management frameworks [7, 68]. An Environmental Evaluation Matrix (EEM) tool has been introduced, which provides information to the gate-reviews about potential areas of environmental concerns relating to projects in the manufacturing sector [66, 68]. The EEM tool is based on a qualitative assessment of the life cycles of assets and products, which are typically the outcome of projects in the manufacturing sector. Quantitative assessment approaches, although available, are of limited use due to inadequate data of the projected environmental performances of the life cycles of assets and products that is typically available in the early stages of projects in the manufacturing sector [66, 68]. Where environmental assessment information is supplied, two different methodologies have been proposed to incorporate the output into the gate-review decision-making process [68], as is shown in Figure 1.12. Sustainable Project LCM is therefore dependent on the effective inclusion of environmental and social issues in the Asset LCM and Product LCM practices of an organisation.

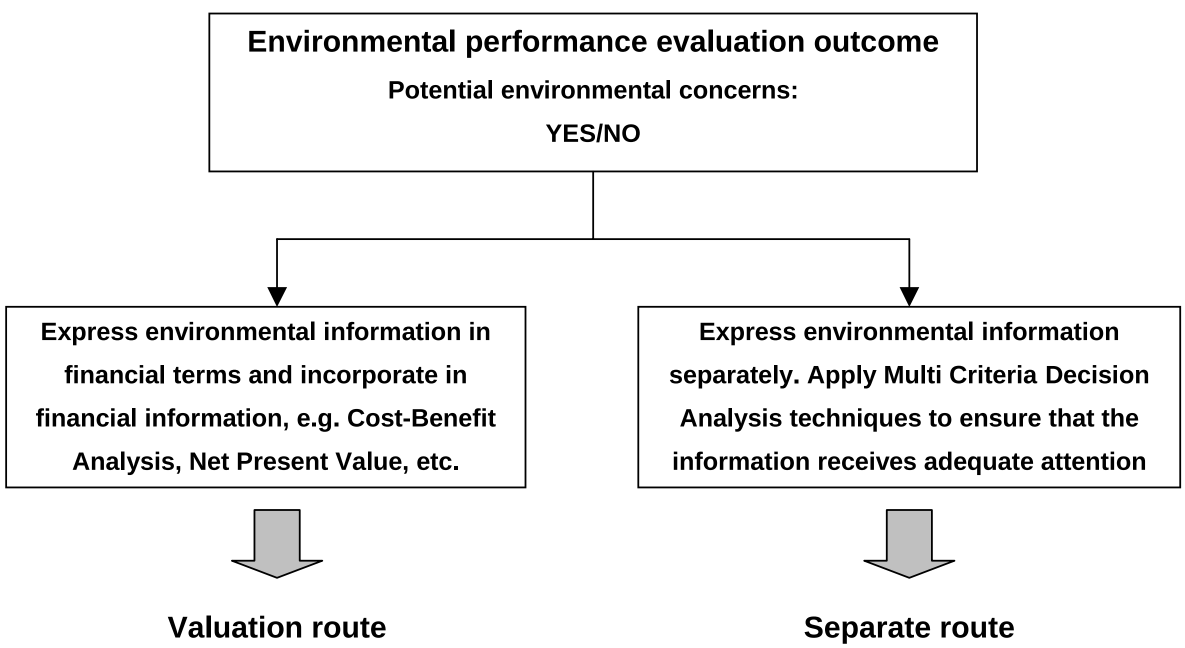

Figure 1.12: Methodologies to incorporate environmental aspects in decisions [68]

1.4.2 Asset Life Cycle Management

An effective asset management strategy has become a focus area of many companies to acquire and sustain a competitive advantage within a global economy. The challenge in managing the entire life cycles of assets in the manufacturing sector effectively typically lies in the fact that costs are isolated and addressed in a fragmented way through the various stages. Figure 1.13 [69] provides a more detailed illustration of the life cycle stages of assets, which are shown in Figure 1.11.

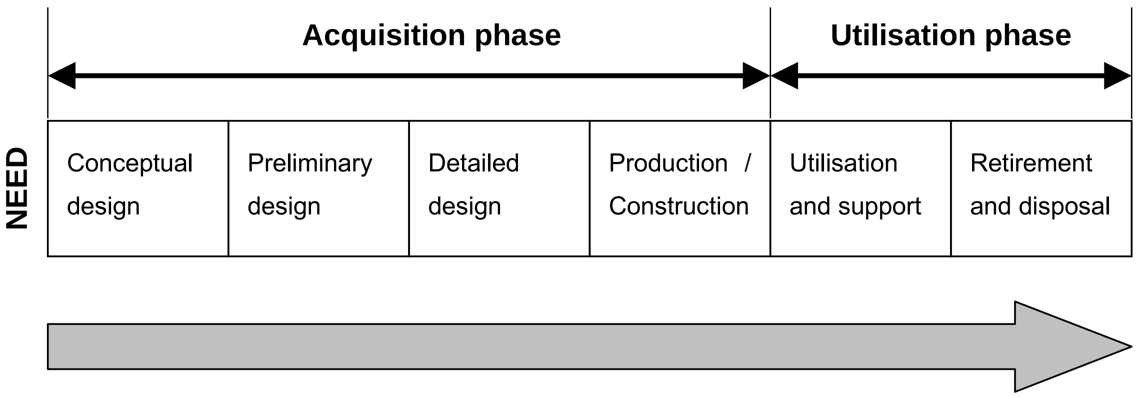

Figure 1.13: Life cycle phases of process asset systems [69]

During the acquisition phase, the emphasis is on implementing a technology within the boundaries of the approved budget and prescribed time frame, while ensuring that the facility conforms to the technical specifications. The primary drivers of the utilisation phase are the associated costs of product distribution, spares and inventory, maintenance, training, etc. It is rarely considered that an estimated 65% of a facility's life cycle costs are fixed during the design phase [70]. Similarly, potential benefits other than costs may be demonstrated in the design phase from a sustainable development perspective, e.g. the elimination of waste or the reduction in energy and water usage [71]. A life cycle model is therefore applied in the design phase, which is application-specific and should [72]:

- represent the characteristics of the asset being analysed including its intended use environment, operating and maintenance support scenarios and any constraints and limitations;

- be comprehensive enough to include and highlight the factors relevant to the asset;
- be easily understood to allow timely decision-making, future updates and modifications; and
- Provide for the evaluation of specific life cycle elements independently from other elements.

A holistic Asset LCM approach incorporates effective environmental management practices and tools with the additional required disciplines of Maintenance Management [73], Systems Engineering [74], Logistics Engineering [69] and Life Cycle Costing [75]. From a sustainable development perspective, an Asset Environmental Management Plan (AEMP) has been proposed to identify, document and address the impacts that assets, and the way they were designed to operate, have on the natural environment [76]. Through such a structured EMS the environmental burdens of the acquisition and utilisation phases of assets are duly considered as part of the manufactured products of a company.

1.4.3 Product Life Cycle Management

The life cycle of a product consists of a chain of processes that includes raw material extraction, production, transportation, use, and disposal of the product, and was illustrated in Figure 1.10 [62]. Each unit process utilises various inputs (natural resources) and outputs (emissions and releases to air, water and land). Only by summing the burdens (and benefits) of all upstream and downstream processes for products, can they truly be evaluated comprehensively from a manufacturer's perspective [62].

Sustainable Product LCM, or product stewardship [50], implies the incorporation of the principles of supply chain management, whereby the manufacturer of a product assumes responsibility for the economic, environmental and societal consequences of supplied components, materials and energy inputs. However, little attention is given to the actual economic and societal influences of suppliers [77]. Rather, the current focus is to increase the environmental performance of the supply chain [77, 78], which originates from the integration of supply chain management and environmental pressures [79]:

- It is recognised that systematic approaches to environmental concerns in buyer-supplier systems are necessary.
- Buyer-supplier relations play an increasingly important role in industrial systems and the strategies of companies.
- External environmental pressures have implications on the internal behaviour of companies in supply chain systems.

Although large manufacturing facilities or customers are exerting pressure on the suppliers, the responses from within the supply chain vary. Supplying companies are often hesitant to invest in environmental innovations, as there is no clear correlation with financial performances. Especially smaller, lower profile suppliers, integral parts of any manufacturing system, lack incentives to improve environmental performance, whereas larger, higher profile suppliers respond positively to considerable pressures from customers [79].

The environmental pressures that are exerted by larger manufacturing facilities are the result of the performance-requirements of these facilities in terms of Environmental Management Systems that have been introduced, e.g. ISO 14000 [38]. Purchasing is one of the key processes assessed by ISO 14000 and the procurement process is progressively more recognised to significantly affect the corporate performance along environmental dimensions [80]:

- Directly, i.e. products acquired from the supply chain increase waste during the storage, transportation, processing, use or disposal of these purchased items, and
- Indirectly, i.e. procured items do not consist of a direct monetary cost solely, but also of an environmental burden associated with producing or manufacturing these items.

For a complex product, e.g. the automobile, the total burden associated with the product is therefore dependent on accumulated internal and external burdens (see Figure 1.14). These burdens can translate to a total cost (purchasing and manufacturing burdens) of the final product or a total environmental impact associated with the product. Improvement approaches for supply chain management have been based on an assessment of environmental performance, and the addition of value, of the supplied item, to the final product [81, 82]. Where a potential for improvement in the supply chain is identified, smaller companies are often assisted through the introduction of technology and operational strategies [83].

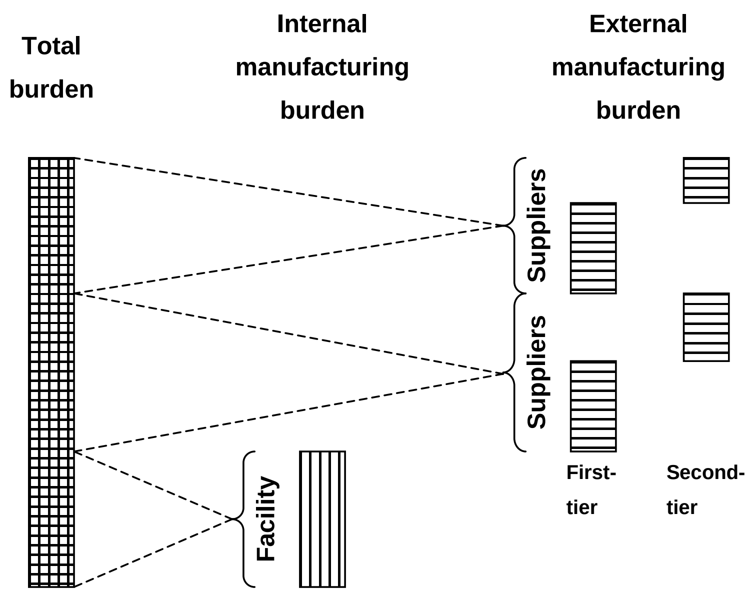

Figure 1.14: Accumulated burdens (economic and environmental) of a product

The lack of environmental data to determine the precise environmental impacts of supplying companies in industry is common in South Africa [10]. In particular, smaller supplying companies in the manufacturing value chain of the South African automotive sector have only restricted process information. Original Equipment Manufacturers (OEMs) have commenced to systematically obtain the restricted information and specifically: water usage, energy usage, and solid waste produced per manufactured item [84]. These three process parameters do not directly show the overall burden of a supplying company on the environmental resources of South Africa. Translating these process parameters into overall environmental burdens, as is shown in Figure 1.15, is the task of the Life Cycle Impact Assessment (LCIA) phase of the total LCM approach.

An LCIA procedure is therefore required to translate the three limited process parameters into specific quantified environmental impacts (or indicators) in the South African context.

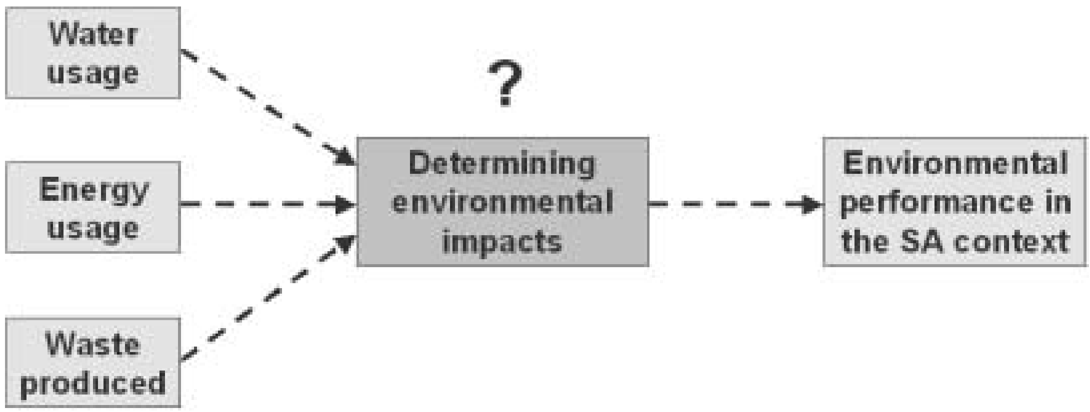

Figure 1.15: Assessing environmental performances from limited parameters

1.5 Conclusion: LCIA and LCM in the South African context

The South African situation needs to be understood for local management and decision support in terms of:

- Economy: the need to increase the export potential whilst addressing the needs of the local consumer market and socio-economic sustainability.
- Technology: technologies that address the needs of the South African society and its sustainability.
- Environment: pressures experienced from economical and technological developments due to the unique ecological characteristics of South Africa.

The latter emphasises that the Life Cycle Impact Assessment (LCIA) phase, as part of the LCA component of LCM, should address specific South African conditions. The LCIA phase in general, as well as specific LCIA procedures that are applied in the South African manufacturing industry, should therefore be evaluated in the South African context, and specifically in terms of four natural resource groups that are addressed in the South African constitution (see Figure 1.16) [85]:

- Water resources, which include quantity and quality aspects to ensure human health and ecosystem quality sustainability.
- Air resources, which focus on regional and global aspects that influence human health and ecosystem quality.
- Land resources, which include quantity and quality considerations.
- Mined abiotic resources, which comprise of non-renewable mineral and energy reserves.

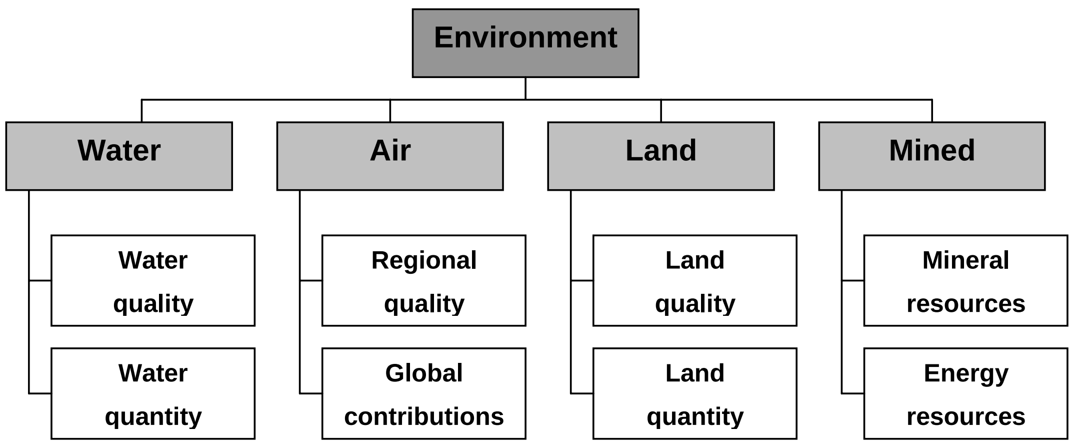

Figure 1.16: A framework to classify environmental impacts of projects [68]

The South African constitution of 1996 (Act 108) stipulates in Section 24 that the quantity and quality of these resource groups must be maintained for society (human health and welfare) and the ecology in general (ecosystem quality) for present and future generations [85]. Furthermore, an evaluation of environmental checklists, sustainable development indicators and environmental performance indicators identified these four main environmental groups as Areas of Protection (AoP) where industrial projects have potential impacts [68]. The primary research question is therefore: Do the LCIA procedures, which are currently used in the South African manufacturing industry, consider the impacts on the quantity and quality of the four natural resource groups equally, especially in terms of human health and welfare, and ecosystem quality? With respect to the LCIA phase of LCM, the secondary research questions are the following:

- Are certain impact categories, critical from a South African natural environmental perspective, often omitted in the classification step (of LCIAs), e.g. water and land availability?
- Are the modelling procedures for characterisation factors (of LCIAs) appropriate for South Africa? For example, the chemical transformation, and pathway and exposure scenarios for air, water and soil pollutants are most probably dissimilar in South Africa compared to Europe.
- Are the normalisation factors (typically used in LCIAs) applicable to South Africa, i.e. do the normalisation values reflect the current ambient state of the impact categories with the (regionally diverse) South African environment as a reference system?
- Are the subjective weighting mechanisms and values (in current LCIAs) a good indication of the importance that the South African society places on different environmental categories?
- Is the combination of LCIA subcomponents or elements adequate to ascertain suitable indicators that can be used for a typical LCM problem, e.g. supply chain management, in South Africa?

The research project subsequently consists of:

- A (qualitative and quantitative) review of the current European LCIA procedures that are used in the South African manufacturing sector in order to identify any potential shortcomings (from a South African perspective) with respect to the emphasis that is placed on different environmental aspects.
- The development of a South African specific LCIA procedure, based on the existing European models, which addresses the potential shortcomings. Specifically, the required region-specificity is addressed, before compiling and demonstrating the developed LCIA procedure.
- The application of the developed model for a South African specific LCM problem, i.e. the evaluation of environmental performances of companies in supply chain management. The LCIA procedure is then compiled in a user-friendly software format for further application purposes in the manufacturing industry of South Africa.

Chapter 2: Literature review of the LCIA phase of LCM

The purpose of this chapter is to provide the theoretical background (as stipulated by the ISO 14040 standard) on which LCIA procedures (or models) that are currently used in the manufacturing sector of South Africa are based. The chapter thereby outlines the steps (or elements) that entail the LCIA phase of LCM, i.e. characterisation, normalisation/grouping and weighting. The chapter addresses a specific objective of the research (based on the research questions), which is to qualitatively review the currently used LCIA procedures (in the South African manufacturing sector) in terms of the:

- adequate assessment of impact consequences of life cycle systems on human health and ecosystem quality from a South African perspective;
- introduction of a comprehensive set of environmental categories that are suitable for environmental assessments in South Africa, specifically with respect to the four natural resource groups stipulated in Chapter 1;
- focus on region-specificity of the calculated indicators, which would differentiate between the diverse eco-regions of South Africa; and
- methods that are used for calculating normalisation and weighting values, with reference to possible methodologies that may be appropriate to establish a South African set of values.

The chapter finally ascertains the potential shortcomings of the published procedures that are based on the ISO standard, especially with respect to the practicality of use in the South African industry.

2.1 Overview of the LCIA phase of LCM

The exact procedure to execute the environmental Life Cycle Impact Assessment (LCIA) phase of an LCA, as a sub-component of LCM, is not stipulated clearly [61] and the scientific community is in disagreement on the methodology to be used [63] and the interpretation of the results that are obtained using different approaches [86].

The complexity of the LCIA procedure lies in the cause-effect chains, linking emissions and resource depletion to the consequences, as is illustrated in Figure 2.1 [87]. These cause-effect chains show that environmental impacts can be described at different impact levels, which include different temporal and spatial scales and types of effects. Table 2.1 uses the example of greenhouse gas releases to show different impact levels [88].

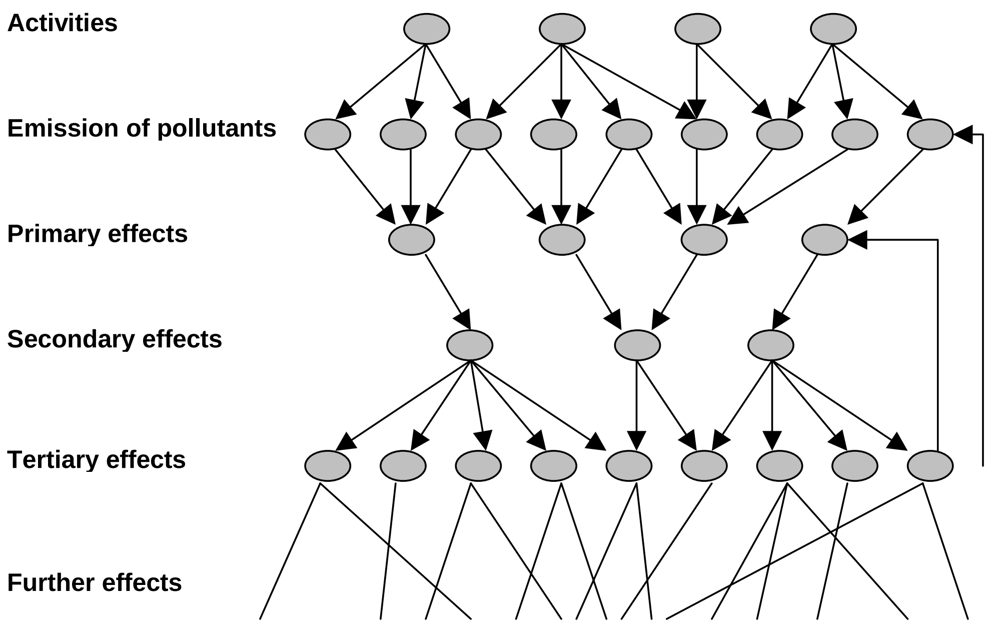

Figure 2.1: Cause-effect chain of environmental impacts [87]

Table 2.1: Different effects of greenhouse gas release impacts [88]

Level	Cause – Effect
Activity	Combustion processes, e.g. electricity generation from coal
Pollutants emitted	Carbon dioxide (CO_2), methane (CH_4), etc.
Primary effect	Radiative forcing, i.e. absorption of thermal infra-red radiation in the atmosphere
Secondary effect	Increase in global temperature
Tertiary effect	Ice-melting, rising sea levels, change in weather patterns
Further effects	Specific changes in ecosystems

Due to the intricacy of evaluating the cause-effect chain of each environmental problem, many LCIA methods have been published that are used by LCA practitioners [89]. The five methods that are most commonly used in the South African manufacturing industry are [90]:

- CML from Leiden University, the Netherlands [91].
- Ecopoints from BUWAL, Switzerland [92].
- Eco-indicators 95 from Pré Consultants, the Netherlands [93].
- Eco-indicators 99 from Pré Consultants, the Netherlands [94].
- EPS from Chalmers University of Technology, Sweden [95].

Although the approaches employed by the different LCIA methods differ, they do comply with the basic requirements as set out by the TC207 technical committee of ISO [61]. These requirements are shown in Figure 2.2. The figure illustrates that all LCA studies must include the two elements of classification and characterisation. The ISO 14042 standard stipulates the considerations that need to be taken into account when executing these two obligatory elements (see Figure 2.3 [61]).

The chosen impact categories differ between the published methods, but Table 2.2 provides a list of possible categories [87], some of which are used by the five methods.

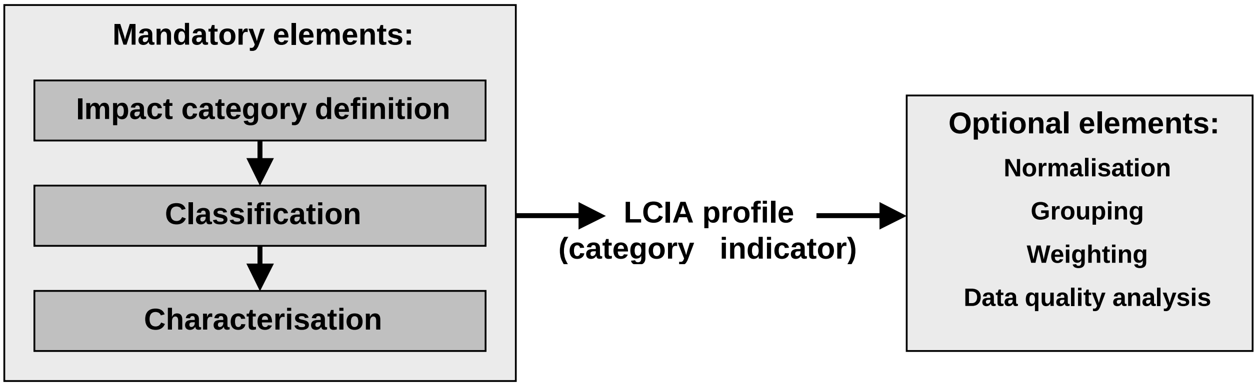

Figure 2.2: Life Cycle Impact Analysis (LCIA) according to ISO 14042 [61]

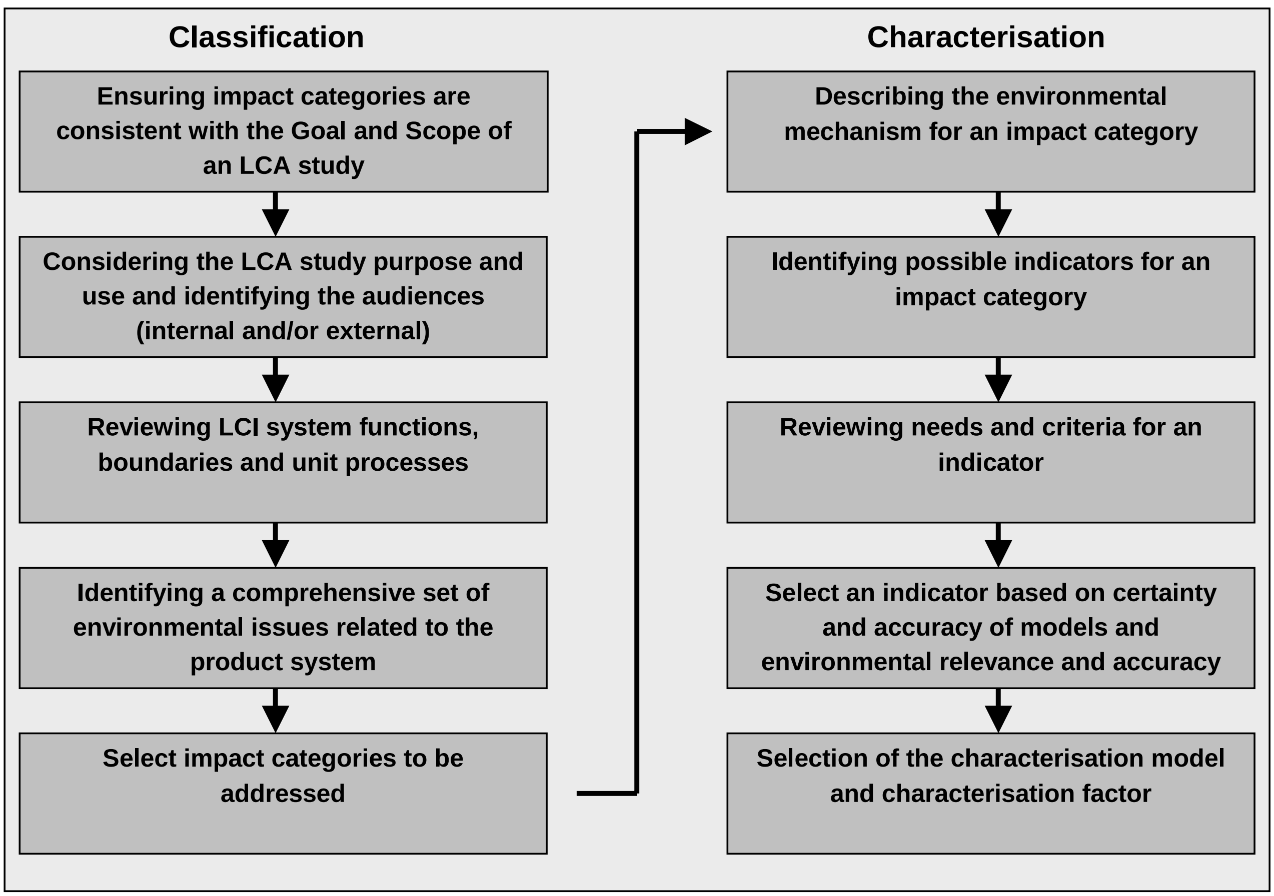

Figure 2.3: Diagram of the steps of classification and characterisation [61]

Table 2.2: List of possible impact categories for LCIA procedures [87]

Main impact category	Sub-impact category
Resources	Energy and materials (can be subdivided) Water Land (including wetlands)
Human health	Toxicological impacts (excluding work environment) Non-toxicological impacts (excluding work environment) Impacts in the work environment
Ecological consequences	Global warming Depletion of stratospheric ozone Acidification Eutrophication Photo-oxidant formation Ecotoxicological impacts Habitat alterations and impacts on biodiversity
Others	Inflows, which are not traced back to the bio-sphere Outflows, which are not followed back to the bio-sphere (these are not actual impact categories, but should be included in the study)

The optional elements of an LCIA are determined by the intended application. For example, when results are intended to compare products and the results are to be presented to the general public, weighting should not be used [61]. However, applying LCA to the Design for Environment (DfE) approach for eco-friendly products emphasises the effectiveness of a single scoring mechanism to compare design changes in-house [96]. DfE is becoming increasingly important where product stewardship is incorporated into the decisions of designers [50]. A single scoring mechanism requires the LCIA to include a weighting procedure, as is shown in Figure 2.4 [97]. In the figure, midpoints refer to the sub-impact categories of Table 2.2, while endpoints refer to the first column.

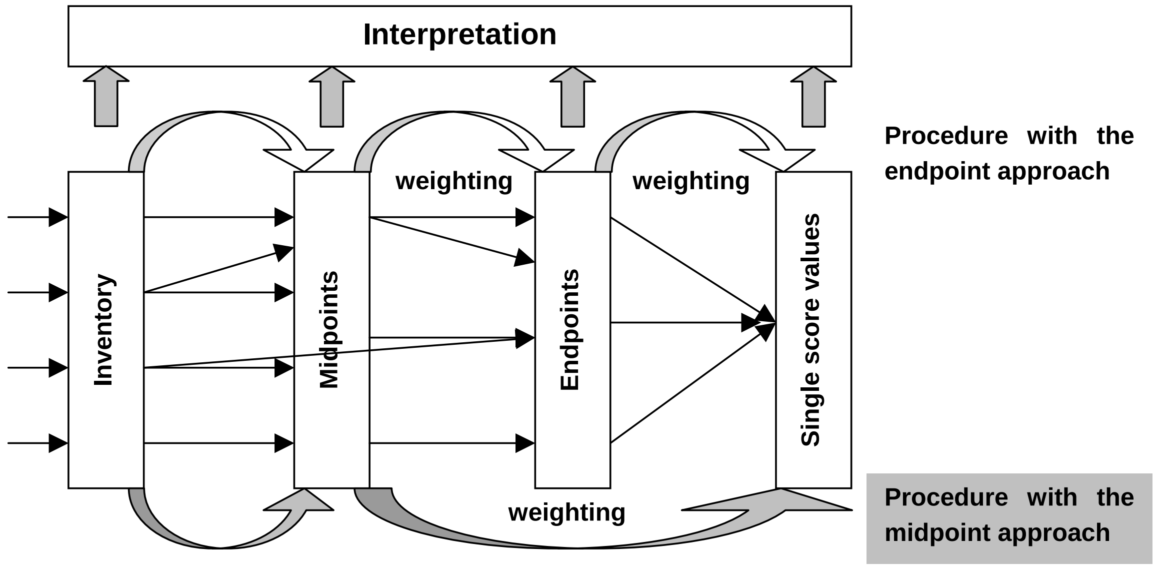

Figure 2.4: Using midpoints and endpoints in a single scoring mechanism [97]

Normalisation is always performed when impact categories are compared before weighting. The ISO 14042 standard defines normalisation as a calculation of the magnitude of the impact category results compared to reference information [61]. It therefore typically requires background or baseline data of the current situation in a studied geographical region, e.g. the total emissions and resources used in a specific country. Normalised impact indicators are thereby calculated through the following equation:

$$I_N = \frac{I_C}{N_C} \qquad 2.1$$

Where: I_N = Normalised environmental impact category

I_C = Calculated impact of a life cycle system in a category

N_C = Normalisation value in a category, e.g. total national emissions

Grouping of impact categories and weighting usually has a political or social element that influences the weighting values. Three weighting procedures are frequently used [98]:

- The panel method, whereby a panel of individuals ranks various impacts. The relative weight of each impact is thereby determined from the combination or aggregation of the opinions of the individuals in the chosen panel.
- The monetary method, whereby an economic cost is placed on the environmental damage caused by an impact. One example of this approach is the willingness-to-pay method, which is derived from the readiness of individuals to pay to avoid a certain environmental impact.
- The distance-to-target method, which is the difference between current levels of environmental impacts and target levels set by LCA practitioners, which are typically based on governmental policy.

The applications of LCA, and the degree to which the optional elements of the LCIA phase (Figure 2.2) are used, have resulted in the five proposed LCIA procedures that are commonly used in the South African manufacturing sector [90]. At a global level there is an attempt to synthesise these and other methodologies through the LCIA framework that is proposed through the Life Cycle Initiative of the United Nations Environmental Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC) [99].

The current LCIA procedures, which are used in South Africa [90], are analysed in greater detail in terms of the characterisation, normalisation and weighting steps. The analysis is based on the following criteria:

- The impact consequences, due to the degradation of water, air, land and mined abiotic resources (see Figure 1.16), are equally addressed in terms of human health and ecosystem quality.
- A comprehensive set of environmental categories are considered that is suitable for environmental assessments in South Africa, i.e. all environmental impacts of a life cycle system on the water, air, land, and mined abiotic resources are duly considered.
- The calculated indicators from the LCIA procedures are region-specific either through the characterisation, normalisation or weighting steps of the procedures.

The LCIA procedures are also specifically analysed with respect to the methods of calculating normalisation and weighting values, in order to identify possible methodologies that may be appropriate in the establishment of a South African set of values (if required).

2.2 CML from the University of Leiden, the Netherlands

2.2.1 Description of the CML methodology

The methodology of the Centre for Environmental Studies (CML) of the University of Leiden was originally published in 1992 [93] and formed the basis for the development of the majority of other LCIA procedures, including the Society of Environmental Toxicology and Chemistry (SETAC) LCA code of practice [100]. The methodology was updated in 2001 [91] and is the most recent of all the LCIA procedures (as at the beginning of 2003). It is compatible with the ISO standard [61] and indicates explicitly where it goes beyond the ISO standard.

The classified impact categories for the characterisation step of the procedure are based on up-to-date scientific principles, as developed within the scientific community of SETAC and its working groups. The method attempts to be unambiguous in terms of these categories, which are shown in Table 2.3.

Table 2.3: Characteristics of the CML LCIA methodology [91]

Impact categories	Units of measurement	Normalisation and weighting
Eutrophication	kg of PO_4^{3-} equivalence of substances	<u>Normalisation</u>
Ozone depletion	kg of CFC-11 equivalence of substances	Choice of normalised values given for:
Eco-toxicity	kg of 1, 4-dichlorobenzene equivalence	
Greenhouse gases	kg of CO_2 equivalence of substances	• World population (1990)
Acidification	kg of SO_2 equivalence of substances	• The Netherlands (1997)
Photo-oxidant formation	kg of C_2H_4 equivalence of substances	• Western Europe (1995)
Human toxicity	kg of 1, 4-dichlorobenzene equivalence	
Energy use	MJ or kg of fuel per MJ	<u>Weighting</u>
Solid waste	kg of waste	No weighting procedure included or recommended.
Abiotic resource depletion	kg of Sb equivalence	
Land use	m^2.yr (increase of land competition)	

Also shown in the table are the units of measurements, and CML differentiates between simplified and detailed procedures to determine these. In certain impact categories, equivalence as a unit of measurement refers to the relative environmental intervention of a released chemical substance (from the life cycle inventory) compared to a specific substance in the given impact category, i.e. based on the chemical properties of evaluated substances. For example, the greenhouse gases impact category refers to the Global Warming Potential (GWP) of different emitted substances. GWP is a simplified indexing system that is based on the radiative forcing properties of different gases and can be used to estimate the potential future impacts of emissions on climate systems [101]. It has been defined as the time-integrated radiative forcing from the instantaneous release of one kilogram of a trace substance relative to that of one kilogram of the reference gas CO_2 [101]:

$$GWP(x) = \frac{\int_0^{TH} r_x \cdot c_x(t) \cdot dt}{\int_0^{TH} r_{CO_2} \cdot c_{CO_2}(t) \cdot dt} \qquad 2.2$$

Where: GWP(x) = Global Warming Potential of substance x

TH = Time Horizon over which the calculation is considered

r = Radiative efficiency due to a unit increase in atmospheric abundance of substance x and CO_2 [$W/m^2/kg$]

c(t) = Time-dependent decay in abundance of the instantaneous release of substance x and of CO_2

Similarly, the other emission categories are fully traceable. In the case of minerals and energy resource depletion, the abiotic depletion potential (ADP) is determined for each mineral and fossil fuel based on the current known concentration-based reserves and rate of de-accumulation. Land-use is defined as occupied land, which is temporarily unavailable as a resource. Solid waste is not directly seen as an environmental intervention, but as a quantity that must be handled economically. CML is cautious to include categories such as these and a number of additional categories, such as odour, noise, etc. are described in the updated documents, but not incorporated into the quantification process. A distinction is therefore made between [91]:

- Interventions that are known to contribute to an impact category, for which no characterisation factor is known but for which a factor can be calculated, estimated or extrapolated.
- Interventions that are known to contribute to an impact category, but for which no characterisation factor can be found, calculated, estimated or extrapolated.
- Interventions assumed to be environmentally relevant but not contributing to any of the selected impact categories.
- Interventions assumed not to be environmentally relevant.

As is shown in Table 2.3, sets of normalisation data are derived for three separate regions, i.e. the Netherlands, Western Europe and the World. CML indicates that a uniform set of regionally specified reference values is lacking and additional data sets are required for the different temporal scales, especially global data, based on empirical measurements and derived statistics. A certain level of uncertainty therefore exists with regards to the proposed normalisation data [102]. In some cases global impact categories are normalised on the basis of global reference values and regional impact categories on the basis of appropriate regional reference values. Where different scales are combined, the CML methodology specifies that:

- only per capita normalisation data should be used;
- normalisation data for regional impact categories should be based on regions where the specific LCA study under consideration takes place; and
- if grouping and weighting is performed, regionally normalised data should be grouped and weighted using regional grouping and weighting methods.

In terms of the latter, CML does not propose or include a specific grouping and weighting procedure and the overall methodology is therefore not applicable for design purposes, i.e. the single-score principle. However, it does specify relevant procedural steps to be taken in a framework of possible decision-making situations, using normalised results. Examples of normalisation values are provided in Table 2.4.

Table 2.4: Annualised factors for normalisation for different reference regions [102]

Impact categories	Units of measurement	The Netherlands (1997)	Western Europe (1995)	The World (1990)
Abiotic resource depletion	kg (Sb eq.).yr^{-1}	1.71×10^{9}	1.06×10^{10}	1.58×10^{11}
Climate change	kg (CO_2 eq.).yr^{-1}	2.51×10^{11}	4.73×10^{12}	4.45×10^{13}
Ozone depletion	kg (CFC-11 eq.).yr^{-1}	9.77×10^{5}	8.03×10^{7}	1.14×10^{9}
Human toxicity	kg (1,4-DCB eq.).yr^{-1}	1.88×10^{11}	7.57×10^{12}	5.71×10^{13}
Eco-toxicity				
Freshwater aquatic	kg (1,4-DCB eq.).yr^{-1}	7.54×10^{9}	5.05×10^{11}	1.98×10^{12}
Marine aquatic		4.26×10^{12}	1.14×10^{14}	9.11×10^{13}
Photo-oxidant formation	kg (C_2H_4 eq.).yr^{-1}	1.82×10^{8}	8.24×10^{9}	1.07×10^{11}
Acidification	kg (SO_4 eq.).yr^{-1}	6.69×10^{8}	2.74×10^{10}	3.13×10^{11}
Eutrophication	kg (PO_4^{3-} eq.).yr^{-1}	5.02×10^{8}	1.25×10^{10}	1.32×10^{11}

2.2.2 Analysis of the CML methodology

The analysis of the CML methodology, based on the criteria stipulated in section 2.1, is summarised in Table 2.5.

Table 2.5: Compliance of the CML methodology to the analysis criteria

Analysis criteria (from section 2.1)	Characterisation	Normalisation	Weighting
Impact consequences[a]	×	×	×
Comprehensive midpoint categories[b]	×	×	×
Region specific	×	√	×

a Refers to endpoint impacts, e.g. human health and ecosystem quality.

b Comparison of the categories with the listed sub-impact category column of Table 2.2.

The methodology does not take into account the consequences or resulting damages of environmental interventions. The published documentation stipulates a comprehensive list of classified impact categories. However, quantified characterisation procedures for all these categories have not been proposed and the key impact category of water as resource has been excluded, although the impact on water quality is taken into account in terms of freshwater and marine aquatic, and freshwater and marine sediment eco-toxicity. A characterisation method for land-use has only been quantified for land competition (baseline) and not for other possible sub-categories, i.e. loss of life-support function and loss of biodiversity. Again, these sub-categories are discussed briefly as a possibility for future inclusion in a quantified methodology.

The characterisation procedure is not region-specific and depending on the chosen method, normalisation can be region specific, i.e. the Netherlands. Weighting is mentioned in the CML guideline documents, but no specific methodology is proposed. The documentation associated with the CML methodology is extremely comprehensive and note should be taken of the details and recommendations where LCIA procedures are to be developed.

2.3 Ecopoints from BUWAL, Switzerland

2.3.1 Description of the Ecopoints methodology

The Ecopoints or Ecofactor methodology was originally developed in 1990 and updated in 1997 by the Swiss *Bundesamt für Umwelt, Wald und Landschaft* (BUWAL). It is based on the ratio of actual pollution and resource (energy) use in Switzerland to critical targets that are derived from Swiss policy. The method is also referred to as the 'distance to target' method, and the Ecofactors are calculated through the following equation [92]:

$$Ef = \frac{1}{F_k} \times \frac{F}{F_k} \times Const \qquad 2.3$$

Where: Ef = Dimensionless Ecofactor or Ecopoint

$1/F_k$ = Normalisation factor

$F/F_k \times Const$ = Evaluation or weighting factor

and: F = Actual Swiss emission or energy use per year

F_k = Critical or target Swiss emission per year

Const = 1×10^{12}/year

The total impact of a life cycle system can then be calculated by the sum of all impacts related to environmental interventions in a given region, according to the following equation:

$$I_S = \sum_{j=1}^{m} I_j \times Ef_j \qquad 2.4$$

Where: I_S = Total impact of the life cycle system

I_j = Impact of environmental intervention

Ef_j = Calculated Ecofactor for the environmental intervention

The environmental interventions refer to the specific impact categories considered by BUWAL for characterisation, which are shown in Table 2.6.

Table 2.6: Characteristics of the Ecopoints LCIA methodology [92]

Impact categories	Units of measurement	Normalisation and weighting
NO_x	g of equivalent NO_x	Normalisation
SO_x	g of equivalent SO_2	The target/critical inventory (mass or energy) for each impact category for Switzerland over one year.
NMVOC	g of each NMVOC substance	
NH_3	g of NH_3	
PM10 dust	g of dust less than 10µm	
CO_2	equivalent g of CO_2 for each substance	The target/critical inventory refers to the aimed level set by the Swiss authorities.
Ozone depletion	equivalent g of CFC-11 for each substance	
Metals into air; Pb, Cd, Zn, Hg	g of the metals Pb, Cd, Zn, Hg	
Metals into water; Cr, Zn, Cu, Cd, Hg, Pb, Ni	g of the metals Cr, Zn, Cu, Cd, Hg, Pb, Ni	Weighting
Metals into soil	equivalent g of Cd for each metal	Calculated as the ratio of actual inventory value to the target/critical inventory value for each impact category.
COD	equivalent g of COD into water	
P	equivalent g of P into water	
N into water	equivalent g of N into water	
AOX	g of Cl^- into water	
Nitrate	g of NO_3^- into soil	
Pesticides	g of each pesticide into soil	
Waste	g of each waste type into soil	
Radioactive waste	cm^3 of each radioactive waste type	
Energy use	MJ or kg of fuel per MJ	

The Swiss policy that determines the target values of the emission impact categories is based on scientifically published modelling, which considers the fate of the emitted substances in the final mediums of air, topsoil and surface water (Figure 2.5) [92].

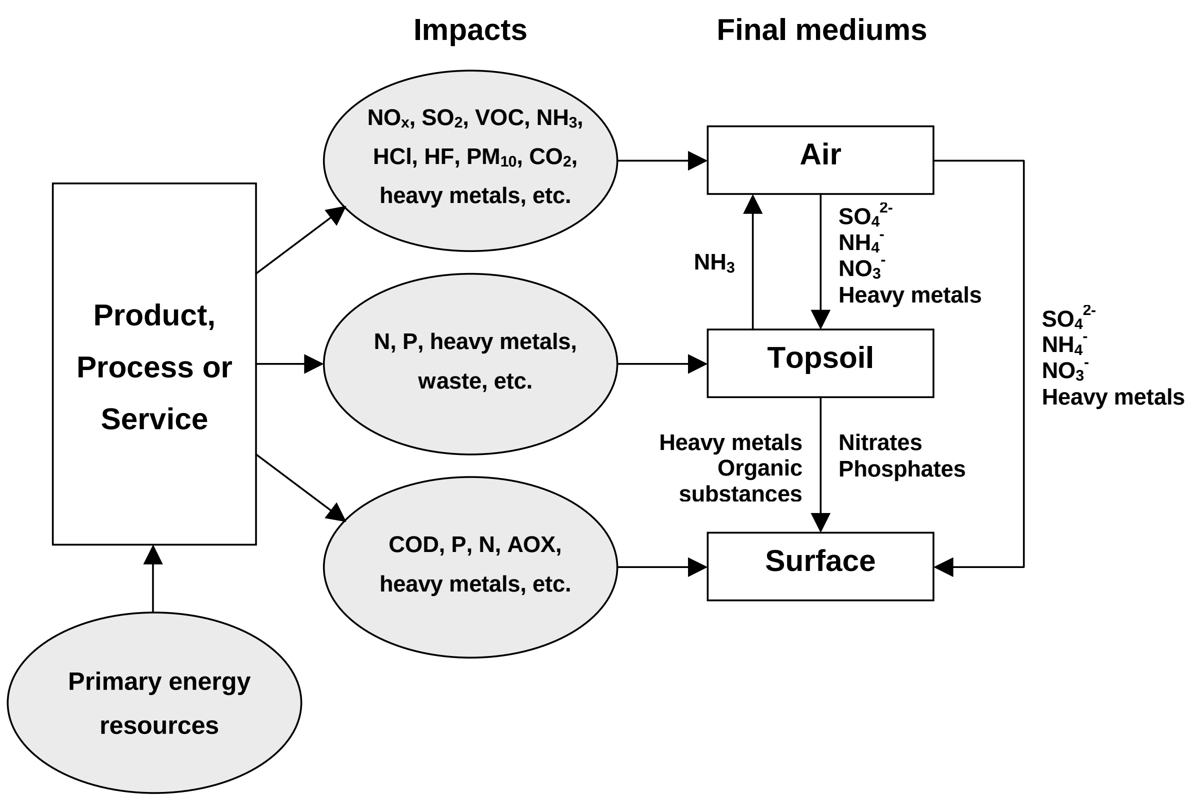

Figure 2.5: Scientific basis for the target values of the Ecopoints procedure [92]

2.3.2 Analysis of the Ecopoints methodology

The analysis of the Ecopoints methodology is shown in Table 2.7. Ecopoints does not consider the impacts of primary energy use and emissions directly. However, impacts influence the Swiss policy and thereby the setting of target values for the normalisation and weighting steps. Although the impact categories are comprehensive with regards to emissions, categories are lacking in terms of resource use if compared to Table 2.2, i.e. abiotic and biotic materials, water and land-use. The modelling to obtain target values (Figure 2.5) is relatively region-specific as they are focused on Switzerland, although uncertainties are encountered during the modelling procedures.

Table 2.7: Compliance of the Ecopoints methodology to the analysis criteria

Analysis criteria (from section 2.1)	Characterisation	Normalisation	Weighting
Impact consequences[a]	×	√	√
Comprehensive midpoint categories[b]	×	×	×
Region specific	√	√	√

a Refers to endpoint impacts, e.g. human health and ecosystem quality.

b Comparison of the categories with the listed sub-impact category column of Table 2.2.

The normalisation and weighting steps require detailed and accurate background inventory data (F in equation 2.3) for the spatial boundaries of the LCA study and complete policy values for specific pollutant categories (F_k in equation 2.3). Both the background data and policy values required by the distance-to-target procedure are limited for South Africa.

The distance-to-target procedure has been criticised in the literature. The setting of target values is rarely transparent [103], as they are often political rather than scientific and are as a consequence agreed upon in a subjective manner [104]. The procedure also assumes that all targets are equally important [105] and it is often viewed as an extension of normalisation, rather than a weighting method [98], i.e. the procedure does not reflect the importance of the different impact categories.

2.4 Eco-indicators 95 from Pré Consultants, the Netherlands

2.4.1 Description of the Ecopoints methodology

The Eco-indicator 95 method was developed under the auspices of the National Reuse of Waste Research Programme (NOH) in the Netherlands [93]. Similar to the Swiss Ecopoints method, Eco-indicators 95 uses the distance-to-target methodology with certain modifications. As opposed to Ecopoints, the Dutch method considers the effects of impacts, rather than the impacts themselves during characterisation. Environmental effects are taken as those effects that cause damage to human health and ecosystems on a European scale:

- Greenhouse effect: the anticipated temperature rise as a result of the increasing concentration of gases that restrict heat radiation by the Earth.

- Ozone layer depletion: the increase in ultraviolet radiation on Earth caused by high-altitude decomposition of the ozone layer.
- Acidification: degradation of forests in particular by, for example, acid rain.
- Eutrophication: the disappearance of rare plants that grow precisely in poor soils, as a result of the emission of substances that have the effect of a fertiliser and the changes in aquatic ecosystems.
- Smog: the problems for people with weak airways (asthma patients) caused by the high concentrations of low-level ozone or by dust and sulphur compounds.
- Toxic substances: substances that are toxic other than as described above, e.g. heavy metals, carcinogenic substances and pesticides.

Table 2.8: Characteristics of the Eco-indicator 95 LCIA methodology [93]

Impact categories	Units of measurement	Normalisation and weighting
Greenhouse gases	kg CO_2	Normalisation
Ozone layer	kg CFC-11	Normalisation is based on 1990 effects levels for Europe excluding the former USSR
Acidification	kg SO_2	
Eutrophication	kg PO_4	
Heavy metals	kg Pb	
Carcinogens	kg B(a)P	Weighting
Winter smog	kg SPM	Calculated as the ratio of actual inventory value to the target/critical inventory value for each effect category, with additional subjective weighting to represent significance.
Summer smog	kg C_2H_4	
Pesticides	kg act.s	
Energy	kg LHV	
Solid waste	kg	

Energy and solid waste were added as effects on ecosystems in terms of energy resource usage and space requirement for waste disposal. Whereas Ecopoints uses target values for normalisation, Eco-indicators 95 uses the extent of the evaluated effects in Europe, i.e. the current contribution of an effect level. This is also consistent with the Society for Environmental Toxicology and Chemistry (SETAC) LCA guidelines [100], which recommends that current values should be used as basis for the calculation of normalisation factors. Apart from the distance-to-target weighting factors, i.e. the ratio of current effects to target values for the effects, Eco-indicators 95 also introduces an additional subjective weighting factor to represent the significance of the effects. The overall calculation procedure is therefore as follows [93]:

$$I = \sum \frac{E_j}{N_j} \cdot W_j \cdot S_j \qquad 2.5$$

Where:	I	= Total eco-indicator (dimensionless) of the system
	E_j	= Effect of an impact category j
	$1/N_j$	= Normalisation factor
	$W_j = N_j/T_j$	= Distance-to-target weighting factor
	S_j	= Subjective weighting factor
and:	N_j	= Total annual effect of a category in Europe per head
	T_j	= Target annual effect of a category in Europe per head

As the normalisation factor Nj is cancelled out in the equation, one should interpret the distance-to-target weighting factors as reduction factors, i.e. the factors by which the current effects need to be reduced to obtain an acceptable effect level. Also, the normalisation step of an LCIA procedure must be clear and separate from the weighting as stipulated by the SETAC guidelines [100].

The equivalence factors used during characterisation are derived from the damages that occur due to the effects. Table 2.9 shows the three damage levels to which effects have been allocated. Acceptable damage levels for these effects have been determined from scientific data, mostly for Europe [106, 107, 108]. These values indicate levels where damages are detectable, but at an acceptable risk level. The ratios of these acceptable levels determine the equivalence factors for emissions or impacts contributing to an effect. Energy and solid waste are not included and are either determined by the energy content of the resource used or the total mass of disposed waste.

Table 2.9: Relationship between effects and damage types [93]

Type of damage	Effects contributing to the damage
Number of fatalities as a consequence of the effect	Ozone layer depletion Airborne heavy metals Pesticides Carcinogenic substances
Nuisance and number of non-fatal casualties as a result of the occurrence of smog periods	Winter smog Summer smog
Damage to parts of the ecosystem	Greenhouse effect Acidification Eutrophication Waterborne heavy metals Pesticides Energy Solid waste

Normalisation is based on published data on anthropogenic emissions and energy use in Europe at the beginning of the 1990s. Europe thus excludes the previous eastern block countries. Where country specific data sets were missing, an extrapolation was made based on the total energy consumption of the country. It was therefore assumed that a country's energy consumption reflects the country's industrial structure and also the emissions patterns. The normalisation calculation also included a division by the total population of Europe, assumed to be 497 million inhabitants. The target values used by the method are based on modelled outputs of scientific data that were used to determine the acceptable damage levels. Eco-points 95 modelling regards the following three damage levels as equal [93]:

- One extra death per million inhabitants per year.
- Health complaints as a result of smog periods (avoidance of smog periods).
- Five percent ecosystem impairment (in the longer term).

This choice relates to the subjective weighting factor of equation 2.5. The parameter S_j has therefore been set to one and the parameter T_j is adjusted accordingly to reflect the significance of the effects. The overall methodology is shown in Figure 2.6.

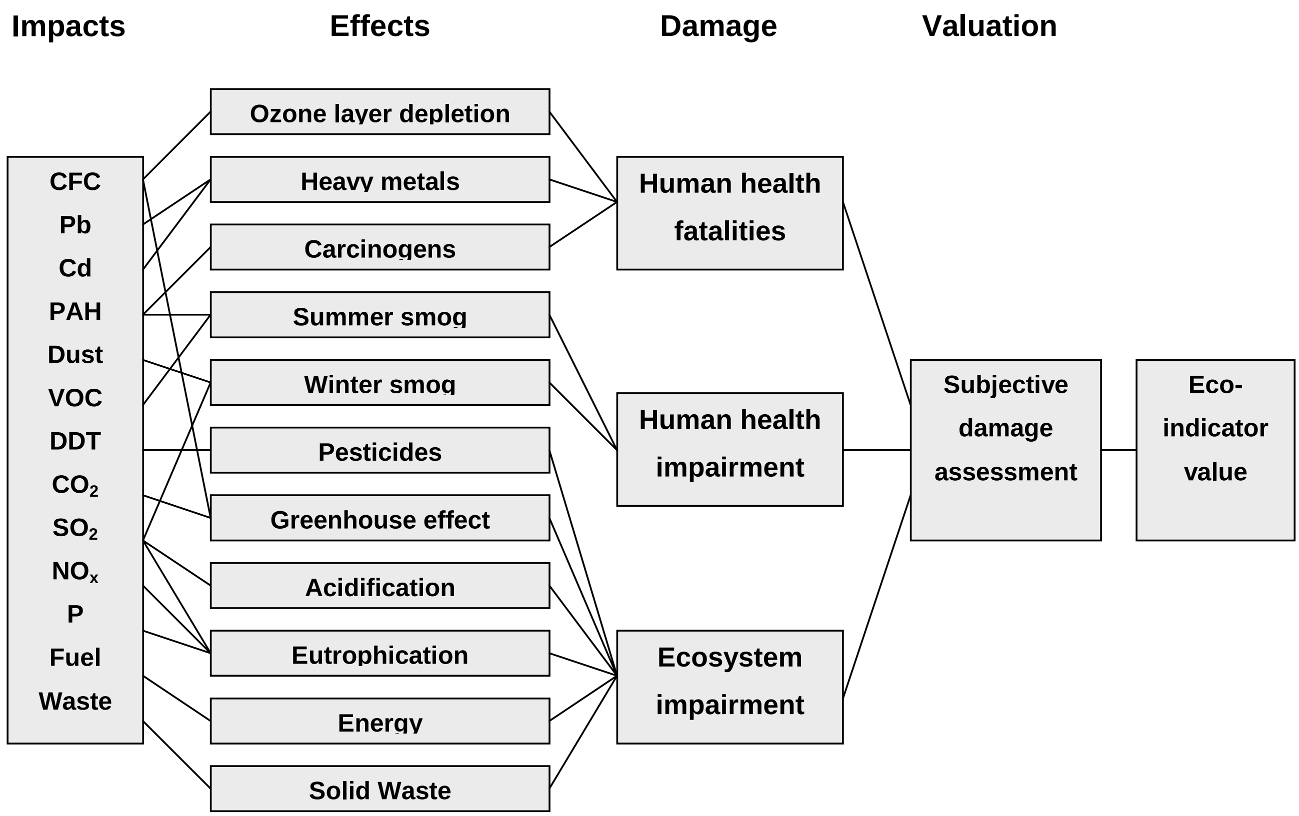

Figure 2.6: Schematic representation of the Eco-indicators 95 procedure [93]

2.4.2 Analysis of the Eco-indicators 95 methodology

The consequences of the impact categories are taken into account with this procedure (Table 2.10). The allocation of effects to damages, however, may be problematic as some of the effects may cause multiple damages. For example, the effect of heavy metals releases may have a human health impact, but also impact on ecosystem quality due to eco-toxicity characteristics. The latter may prove to be of more importance, which will in turn have an influence on the setting of target values. Additional uncertainties exist with determining effects and damages of the categories, but these are associated with scientific fields outside the life cycle impact analysis discipline, e.g. the extrapolation of animal experiments to determine toxicity levels for humans.

Table 2.10: Compliance of the Eco-indicators 95 methodology to the analysis criteria

Analysis criteria (from section 2.1)	Characterisation	Normalisation	Weighting
Impact consequences[a]	√	√	√
Comprehensive midpoint categories[b]	×	×	×
Region specific	×	×	×

a Refers to endpoint impacts, e.g. human health and ecosystem quality.

b Comparison of the categories with the listed sub-impact category column of Table 2.2.

Certain impact categories are omitted from the methodology as it is focussed on a European scale, specifically water, land and minerals as resources. Reasonable background inventory data is required for normalisation, and as the procedure is not region specific, a high level of uncertainty exists where the energy extrapolation has been used to fill missing data. Although region-specific inventory data could be used for normalisation, this would not be inconsistent with the remainder of the method, which considers damages at a European scale.

The typical problems associated with the distance-to-target procedure (see Section 2.3.2) have been dealt with through the introduction of a significance factor. Albeit subjective, the subjectivity is explicitly formulated and less prejudiced than other weighting procedures, e.g. the conventional panel method on which the Eco-indicators 99 methodology is based.

2.5 Eco-indicators 99 from Pré Consultants, the Netherlands

2.5.1 Description of the Eco-indicators 99 methodology

The Eco-indicators 99 project was commissioned by the Dutch Ministry of Housing, Spatial Planning and the Environment (VROM) in order to update the Eco-indicators 95 methodology. The primary differences of the Eco-indicators 99 method compared to the previous version lie in the characterisation and weighting steps. The effects are allocated to three endpoint categories, i.e. human health, ecosystem quality and resources, with units of measurements directly indicating the damages to these endpoints (Table 2.11) [94].

Table 2.11: Characteristics of the Eco-indicator 99 LCIA methodology [94]

Impact categories	Units of measurement	Normalisation and weighting
Human health Carcinogenic emissions Respiratory organics Respiratory inorganics Climate change Radiation Ozone layer depletion	DALYs of substances in sub-categories A DALY (Disability Adjusted Life Years) is calculated for each emission into air, water and soil in these sub-categories. Links health effect to the number of years lived disabled and years of life lost.	Normalisation Total inventory of mass and energy used (mostly for 1993 as base year) for the whole of western Europe for one year per person (population of 495 million assumed).
Ecosystem quality Eco-toxicity Acidification/Eutrophication Land use	PDF of substances/cause in sub-categories Links effects to Potentially Disappeared Fraction (PDF) for plants.	Weighting A choice of four based on responses from a panel of experts placed into three perspectives: • Individualists (higher weight to human health • Egalitarians (higher weight to ecosystem quality) • Hierarchists (equal weight distribution)
Resources Minerals Fossil fuels	MJ surplus for each resource Links lower concentration to increased efforts to extract resources in future	

The contributions of effects to the three endpoint-categories are the result of extensive modelling to connect damages to life cycle inventory results. Human health modelling is expressed in the Disability Adjusted Life Years (DALYs) scale, which was developed for the World Health Organization (WHO) and the World Bank [109], and consists of the following steps [94]:

- Fate analysis: linking an emission to a temporary change in ambient concentration.
- Exposure analysis: linking the ambient concentration to a dose intake.
- Effects analysis: linking the dose to a number of health effects.
- Damage analysis: linking health effects to DALYs.

Ecosystem quality modelling is expressed as a Percentage Disappeared Fraction (PDF) of species in a certain area due to an environmental load. The modelling procedure is not homogeneous as with human health and the three effects that are allocated to this damage endpoint are treated separately [94]:

- Eco-toxicity is expressed as a Percentage Affected Fraction (PAF) of certain terrestrial and aquatic species under toxic stress. A conversion factor is proposed to translate toxic stress to observable damage.
- Acidification and eutrophication are combined and the observable disappearance of vascular plants in the Netherlands is used as a basis for the modelling.
- Land-use and land transformation is based on empirical data of the occurrence of vascular plants in the Netherlands as a function of the land-use type and the size of the area. Local and regional damages to ecosystems are taken into account in the modelling.

The resource damage category is expressed as surplus energy, which is the expected increase of energy required per kilogram of extracted material after a period when the amount of material that has been extracted is equal to five times the cumulative extracted material prior to 1990. The chosen figure of five is subjective and the absolute value of the surplus energy has little meaning.

Similar to the previous Eco-indicator methodology, normalisation factors are determined at a European scale. Normalisation is executed directly on the effects categories relating to the damage endpoint-categories of human health, ecosystem quality and resources, which the ISO 14042 standard does allow [61].

The weighting procedure follows a panel procedure amongst a Swiss LCA interest group, which was requested to rank the three endpoint-categories in order of importance. The response from the panel has been discriminated as adhering to three cultural perspectives [94]:

- Egalitarian: with a long-term perspective, where a minimum of scientific proof justifies the inclusion of an effect.
- Individualist: with a short-term perspective, where only proven effects are included.

- Hierarchist: with a balanced time perspective, where consensus amongst scientists determines the inclusion of an effect.

The suggested procedure is to use the average of the panel result as weighting. Thereafter the three cultural perspectives are used as sensitivity analysis of the final score. The weighting values for the three alternatives are shown in Table 2.12 below. The overall procedure is illustrated in Figure 2.7 [110] and can be formulated as follows:

$$I = W_{HH}\sum_{HH}\frac{D_j}{N_j} + W_{EQ}\sum_{EQ}\frac{D_j}{N_j} + W_R\sum_{R}\frac{D_j}{N_j} \quad 2.6$$

Where:

	I	= Total eco-indicator (dimensionless) of the system
	D_j	= Damage of a category j on the endpoints HH, EQ, R
	N_j	= Total annual damage of a category in Europe per head
	W_{HH}	= Weighting factor for the human health endpoint category
	W_{EQ}	= Weighting factor for the ecosystem quality endpoint category
	W_R	= Weighting factor for the resources endpoint category

Table 2.12: Estimate of rounded weighting factors per cultural perspective [94]

	Average	Individualist	Egalitarian	Hierarchist
Ecosystem quality	40 %	25 %	50 %	40 %
Human health	40 %	55 %	30 %	30 %
Resources	20 %	20 %	20 %	30 %

2.5.2 Analysis of the Eco-indicators 99 methodology

The Eco-indicator 99 procedure is internally consistent and traceable in its modelling, providing values of technical uncertainty. The model has uncertainties in terms of:

- data uncertainties, specified for most damage factors as a squared geometric standard deviation; and
- uncertainties about the correctness of the models used, coupled with subjective choices in the models; these subjective choices are the consequence of a

cultural theory approach to quantify modelling assumptions that cannot be avoided.

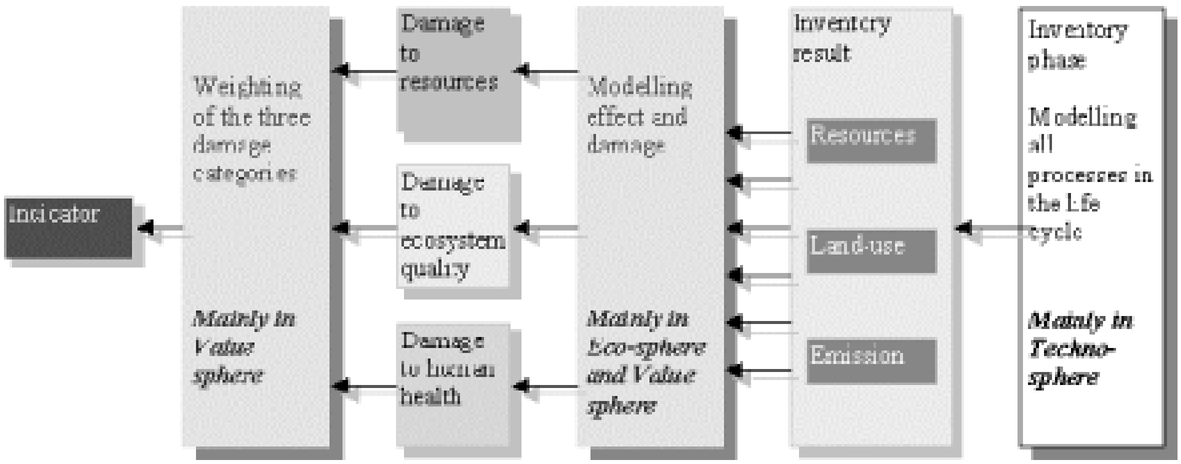

Figure 2.7: Schematic representation of the Eco-indicators 99 procedure [110]

These uncertainties relate to the complexity of the scientific models that are used and the number of steps. As an example, the modelling of damage to human health requires four separate steps, each describing a specific field of science with particular uncertainties. In some of these cases, especially toxicity, it is stated that these uncertainties can be substantial [94].

The list of categories used during the characterisation step is reasonably comprehensive with the only missing parameter being that of water usage (see Table 2.13). However, the modelling procedures for effects categories associated with ecosystem quality and resource extraction are not founded on internationally accepted methodologies and data, and therefore not as plausible and complete as those of human health. Additionally, the modelling, especially that of ecosystem quality, is specific for Europe (and the Netherlands) and therefore not applicable to other parts of the world.

The weighting step of the Eco-indicators 99 methodology is plausible in that it uses a "mixing triangle" that can be used to build consensus, rather than producing simplified answers. This reduces the subjectivity of conventional panel approaches and can be used to test the robustness of a single score result.

Table 2.13: Compliance of the Eco-indicators 99 methodology to the analysis criteria

Analysis criteria (from section 2.1)	Characterisation	Normalisation	Weighting
Impact consequences[a]	√	√	√
Comprehensive midpoint categories[b]	√	×	×
Region specific	×	×	×

a Refers to endpoint impacts, e.g. human health and ecosystem quality.

b Comparison of the categories with the listed sub-impact category column of Table 2.2.

2.6 EPS from Chalmers University of Technology, Sweden

2.6.1 Description of the EPS methodology

The Environmental Priorities Strategies (EPS) methodology was originally developed in 1996 by the Swedish Environmental Research Institute (IVL) for Volvo and updated in 1999 by Chalmers University of Technology [95]. The EPS system was developed as a tool for a company's internal product development process. Similar to the Eco-indicators 99 method, EPS considers endpoint damages. However, these damages are not grouped into endpoint categories but are shown directly in the characterisation phase with separate units of measurement for each effects category (see Table 2.14).

In addition to the scientific modelling of potential effects, e.g. toxicity, additional factors, referred to as corrections, are used to determine damages of the impact categories. These corrections include [95]:

- Exposure: the number of people who actually come into contact with the substance or phenomenon, e.g. the population exposed to the danger of flooding in the event of a rise in the level of the sea.
- Frequency: the number of times that an effect occurs or the probability that it will do so, e.g. a flood caused by a rise in the level of the sea.
- Period: the time for which an effect occurs, including the speed with which a substance degrades.

Table 2.14: Characteristics of the EPS LCIA methodology [95]

Impact categories	Units of measurement	Normalisation and weighting
Years of Life Lost (YOLL)	Reduction in life expectancy	Normalisation
Severe morbidity	Suffering, including starvation	No formal normalisation introduced into method.
Morbidity	Non-severe, e.g. cold or flue	
Severe nuisance	Causing action to avoid nuisance	
Nuisance	Irritating, but not causing action	Weighting
Crop production capacity	kg weight at harvest	Calculated as the willingness to pay (WTP) to restore impacts, where the environmental reference is the present state of the environment.
Wood production capacity	kg dry weight	
Fish and meat capacity	kg full weight of animals	
Base cat-ion capacity	H^+ mole equivalence	
Irrigation water capacity	kg acceptable in terms of persistent toxins	
Drinking water capacity	kg drinking water fulfilling WHO criteria	The indicator unit is the Environmental Load Unit (ELU).
Abiotic resource depletion	kg of elemental, mineral or fossil reserves	
Biodiversity	Normalised extinction of species (NEX)	

Similar to the Eco-indicators 99 methodology, the modelling procedure attempts to base the endpoint damages on scientific principles, which substantially increases the complexity of the procedure. In general, the EPS procedure is not very clearly described and documented in the public domain. It assumes that society places a certain value on five aspects that are termed safeguard subjects and to which the impact categories relate [95]:

1. Resources: the depletion of resources.
2. Human health: the loss of health and the number of extra deaths as a result of the environmental effects.
3. Production: the economic damage of the environmental effects (particularly in agriculture).
4. Biodiversity: the disappearance of plant or animal species.
5. Aesthetic values: the perception of natural beauty.

Using these safeguard subjects, the damages are expressed in financial terms. The valuation is based on three different principles [95]:

- Raw materials depletion is valuated from the future extraction costs of raw materials. For fossil fuels, these are the costs of obtaining a similar fuel if the raw materials resources have been depleted. For example, for oil it is the cost of rapeseed oil production, while the price of wood is used to valuate coal. In the case of minerals, market prices are used.

- The production losses are measured directly from the estimated reduction in agricultural yields and industrial damages, e.g. from corrosion.
- The other three safeguard subjects are valuated in terms of the willingness-to-pay (WTP) principle. WTP relates to the costs society is prepared to compensate for these safeguard subjects. A Contingent Valuation Method (CVM) was used to measure WTP values, and is based on an interviewing procedure comparable with the panel methodology of Eco-indicators 99.

It is implicitly assumed that these three value judgements are interchangeable. However, the processes of obtaining the actual values are not transparent. The single score of the method is found by adding the financial values calculated and is expressed in terms of Environmental Load Units (ELUs). The method, therefore, does not include formal normalisation. The overall method is summarised in Figure 2.8 [95]. EPS uses complex sensitivity analysis methodology to assist a product designer or user to determine the preference of alternatives.

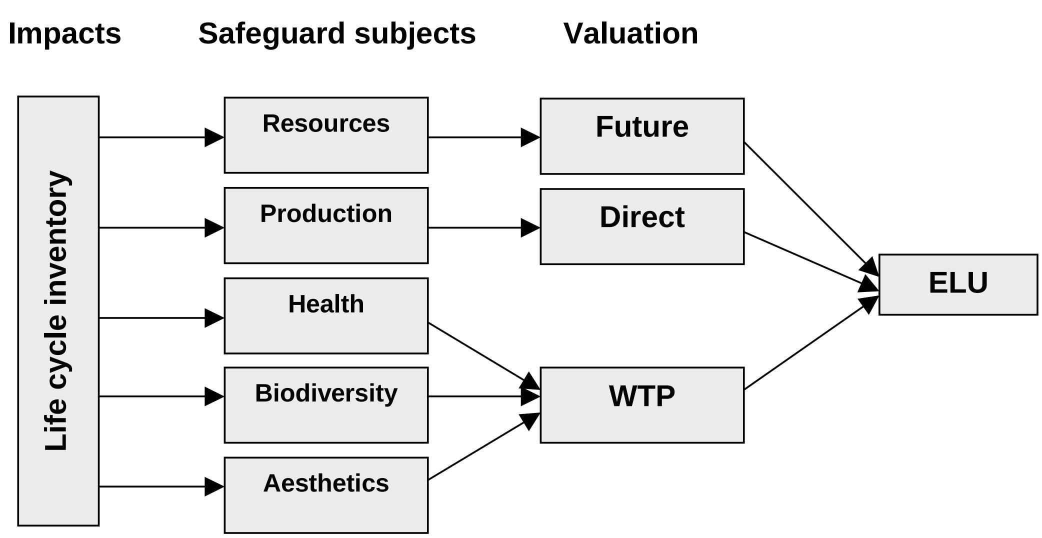

Figure 2.8: Schematic representation of the EPS procedure [95]

2.6.2 Analysis of the EPS methodology

The EPS methodology maintains that the damages of impacts at the endpoint are reasonably addressed on a scientific basis in the characterisation phase (Table 2.15). However, the modelling of the damages is not transparent. Although the impact categories are reasonably comprehensive, the assignment of life cycle inventory parameters to these categories is not apparent. The arguments for the units of measurement of certain damage categories are questionable, e.g. normalised extinction of species for biodiversity implies that particular species have completely disappeared, whereas impact analysis procedures should typically indicate where species disappearance could occur.

Table 2.15: Compliance of the EPS methodology to the analysis criteria

Analysis criteria (from section 2.1)	Characterisation	Normalisation	Weighting
Impact consequences[a]	√	×	√
Comprehensive midpoint categories[b]	√	×	×
Region specific	√	×	√

a Refers to endpoint impacts, e.g. human health and ecosystem quality.

b Comparison of the categories with the listed sub-impact category column of Table 2.2.

While the ISO 14042 standard [61] requires a defined normalisation step, it is not included in the EPS methodology and the final score is not dimensionless but expressed in financial terms. The practical usability of EPS depends greatly on the availability and reliability of the large number of weighting factors that are required and that the willingness-to-pay (WTP) principle is ambiguous. The overall methodology is intrinsically complex and very region specific, i.e. for Scandinavia.

However, note should be taken of the principles by which the EPS system was developed, as these could be beneficial for further procedure improvement:

- Top-down principle: where the highest priority is given to the usefulness of the system, i.e. address those issues that are important to decision makers first and subsequent aspects thereafter.

- Index and default principles: requiring convenient operative default indices for materials and processes representing weighted and aggregated impacts, i.e. little knowledge of environmental impacts required by users.
- Uncertainty principle: requiring the uncertainty of input data to be estimated, i.e. a good sensitivity analysis procedure must be included with associated default data and models.

2.7 LCIA procedures in the South African context

The sustainability challenges for South Africa are unique when compared to other parts of the world [10]. Apart from social and economic dissimilarities associated with a developing country, environmental aspects differ significantly from the European continent where the LCIA procedures (commonly used in South Africa) were developed. The five LCIA procedures reviewed in this chapter are outlined in Table 2.16 and the environmental criteria considered by these procedures are summarised in Table 2.17.

Within the South African context it has been shown that an LCIA procedure should evaluate the impacts equally on four main environmental resource groups, including sub-groups (see Section 1.5 and Figure 1.16): Water Resources, Air Resources, Land Resources, Mined Abiotic Resources [68, 85]. In Table 2.17, the impact categories classified by the five LCIA procedures have subsequently been grouped into air, water, land and mined abiotic resources.

The three resource groups of air, water and land have been further divided into the characteristic human health and ecosystem quality criteria as taken into account by these procedures, either in the characterisation phase (CML, Eco-indicators 95 and 99, and EPS) or in the setting of target values for weighting purposes (Ecopoints and Eco-indicators 95).

Table 2.16: Summary of the approaches of the LCIA procedures

LCIA procedure	Classification and Characterisation	Normalisation and Weighting
CML	**Classification** Relating to issues of concern from a European and global perspective. **Characterisation** Fate and relative environmental intervention (e.g. exposure or depletion) modelling (European continent except for global interventions) of an inventory constituent compared to a specific substance or parameter.	**Normalisation** Choice of normalised values given for: • World population (1990) • The Netherlands (1997) • Western Europe (1995) **Weighting** No weighting procedure included or recommended.
Ecopoints	**Classification** Relating to issues of concern from a Swiss and global perspective. **Characterisation** Fate and relative environmental intervention (e.g. exposure or depletion) modelling (Switzerland and European continent except for global interventions) of an inventory constituent compared to a specific substance or parameter.	**Normalisation** The target/critical inventory (mass or energy) for each impact category for Switzerland over one year. The target/critical inventory refers to the aimed level set by the Swiss authorities. **Weighting** Calculated as the ratio of actual inventory value to the target/critical inventory value for each impact category.
Eco-indicator 95	**Classification** Relating to issues of concern from a Netherlands and global perspective. **Characterisation** Fate and relative environmental intervention (e.g. exposure or depletion) modelling (the Netherlands and European continent except for global interventions) of an inventory constituent compared to a specific substance.	**Normalisation** Normalisation is based on 1990 effects levels for Europe excluding the former USSR. **Weighting** Calculated as the ratio of actual inventory value to the target/critical inventory value for each effect category, with additional subjective weighting to represent significance on human health and ecosystem impairment from a Netherlands perspective.
Eco-indicator 99	**Classification** Relating to human health, ecosystem and abiotic resource damage concerns from a Netherlands and global perspective. **Characterisation** Actual damage modelling (the Netherlands and European continent except for global interventions) of an inventory constituent on human health (Europe), ecosystems (the Netherlands) and mineral and energy resources (global).	**Normalisation** Total inventory of mass and energy used (mostly for 1993 as base year) for the whole of western Europe for one year per person (population of 495 million assumed). **Weighting** A choice of four based on responses from a panel of European scientific experts placed into three perspectives: • Individualists (higher weight to human health) • Egalitarians (higher weight to ecosystem quality) • Hierarchists (equal weight distribution)
EPS	**Classification** Relating to human health, biotic and abiotic resource damage concerns from a Swedish and global perspective. **Characterisation** Actual damage modelling (Sweden and European continent except for global interventions) of an inventory constituent on human health, biotic and abiotic resources.	**Normalisation** No formal normalisation introduced into method. **Weighting** Calculated as the willingness to pay (WTP) to restore impacts, where the environmental reference is the present state of the environment (Swedish perspective). Overall indicator is the Environmental Load Unit (ELU)

Table 2.17: Summary of environmental criteria considered by LCIA procedures

	CML	Ecopoints	Eco-indicators 95	Eco-indicators 99	EPS
Air pollution:					
Human health	√	√	√	√	√
Ecosystem quality	√	√	√	√	√
Water categories:					
Human health	√	√	×	√	√
Ecosystem quality	√	√	√	√	√
Land categories:					
Human health	×	×	×	×	×
Ecosystem quality	√	×	×	√	√
Mined abiotic resources	√	√	×	√	√

Air pollution criteria are covered comprehensively by all the methods and especially human health impacts, due to exposure to air pollution, are dealt with in detail. Impact categories and procedures (for characterisation) relating to air pollution and human health are typically applicable in South Africa as the applied models are not country-specific. However, care must be taken where exposure modelling is included in a procedure as meteorological conditions usually influence results. Similarly, dose-response modelling could be erroneous due to different cultural lifestyles of South African communities, e.g. diet, reliance on home-grown food, etc. Correspondingly, the characterisation modelling of human health impacts due to water quality reduction could possibly be applied in South Africa if it is not country-specific, although cultural differences will have to be taken into account.

The relevance of the methodologies is problematic where categories are used that impact ecosystem quality, as ecosystems differ significantly between South Africa and the European continent on which the methodologies are based. Although all the methods address ecosystem quality to some degree for water and air pollution, the comprehensiveness of these categories varies considerably, e.g. water salinity is an important impact of South African industries on ecosystems, but is not specifically addressed separately. Also, water quantity is only taken into account by one method (EPS) and is almost certainly a vital aspect in a comparatively dry country such as South Africa. The impact of land use and soil emissions on ecosystem quality is also incorporated into some of the procedures to varying degrees. However, land as a potential resource for agriculture and biodiversity conservation is important, and the applicability of the methods, for the South African situation, appears limited in this respect.

Depletions of mined abiotic resources, i.e. minerals and energy, are not localised impacts, although the depletions may be of concern at a national level. These environmental categories, and subsequent characterisation factors, are consequently not region-specific and the current LCIA procedures are probably adequate for life cycle evaluation purposes in South Africa. However, the relative importance of different mineral and energy resources should be reflected in the normalisation step of a South African specific LCIA procedure.

The normalisation and weighting principles of the reviewed LCIA procedures could also be challenging when applied to the South African situation. Normalisation of all the procedures, except Ecopoints (target values) and EPS (no normalisation), requires background emissions and abiotic resource use data. This kind of background data is limited in South Africa for the classified impact categories. None of the normalisation procedures consider the actual ambient state of the environmental categories (and the four natural resource groups) in order to preserve human health and ecosystem quality. This sort of background data is more obtainable (and region-specific) in South Africa. With respect to the particular weighting mechanisms the following can be deduced in terms of the calculated values:

- Distance-to-target methodology: the scientific and policy values used might not be applicable in South Africa, as authorities weight certain environmental aspects differently depending on the current strain on the resources in separate regions.
- Panel methodology: the societal and cultural preferences in South Africa may differ significantly from those in Europe, e.g. due to the scarcity of the resource,

a much higher weight will be placed on water resources compared to air resources. This is proven in Chapter 6.

- Willingness-to-pay methodology: other sustainability criteria (socio-economic and economic) outweigh environmental aspects and parts of society may not deem the environment as economically important [111].

2.8 Conclusions and research rationale

A qualitative review of the commonly used LCIA procedures in the South African manufacturing sector indicates that:

- Certain impact categories, critical from a South African natural environmental perspective, are often omitted in the classification step (of LCIAs), e.g. water usage.
- The modelling procedures for characterisation factors (of LCIAs) are appropriate for South Africa for some of the environmental categories, especially where basic scientific principles are used such as the chemical characteristics of substances. Where characterisation values for air, water and land quality reduction (in terms of impacts on human health) are calculated, the modelling procedures may be appropriate although specific exposure and dose-response modelling in the South African context may be erroneous. Characterisation values that are based on the impacts on ecosystem quality will definitely be invalid in the South African context. Characterisations for water and land quantity impacts are either not addressed, or are incorrect for South Africa. From the qualitative evaluation, the characterisation of mineral and energy resource depletion appears to be suitable for South Africa.
- The normalisation factors that are typically used in LCIAs are not applicable to South Africa, and the normalisation values do not reflect the current ambient state of the impact categories with the (regionally diverse) South African environment as a reference system.
- The subjective weighting mechanisms and values (in separate LCIA procedures) may not be a good indication of the importance that the South African society places on different environmental categories. However, a combination of mechanisms could be used to determine South African applicable values.

A quantitative evaluation will further assist to comprehend the classification, characterisation, normalisation and weighting methodologies of the five reviewed LCIA procedures. A suitable Life Cycle Inventory (LCI) of a South African life cycle system is therefore required, which can be quantitatively evaluated with the current LCIA procedures in terms of impacts on air, water, land and mined abiotic resources. The quantitative results would then indicate which elements of a comprehensive LCIA procedure must be developed further to evaluate the environmental impacts of the manufacturing sector in the South African context.

After a country-specific LCIA model for South Africa is developed, which adequately addresses the impacts on the four natural environmental resource groups that are important from a South African Life Cycle Management perspective, i.e. Water, Air, Land, and Mined Abiotic Resources, a management application of the developed LCIA model can be demonstrated in the local manufacturing sector.

Chapter 3: Quantitative comparison of the current LCIA procedures

This chapter describes a detailed case study of a suitable life cycle system in South Africa that is based on the Streamlined or Screening Life Cycle Assessment (SLCA) methodology [112]. The case study compiles a comprehensive Life Cycle Inventory (LCI) as per the requirements of the ISO 14040 standard (see Figure 1.8 of Chapter 1). The manufacturing of dyed two-fold yarn is used for this purpose. The reason for the choice of this cradle-to-gate life cycle system is that significant impacts on all four the natural resource groups (Water, Air, Land, and Mined Abiotic) occur along the life cycle of the product, and the environmental impacts of the textiles industry is of concern in South Africa and has subsequently received attention [111]. The LCI is used to quantitatively evaluate and compare the five LCIA procedures, which were reviewed in Chapter 2, in order to identify any potential further shortcomings (from a South African perspective) with respect to the emphasis that is placed on the different environmental factors. Thereafter, recommendations are made to develop a new LCIA procedure that better reflects the impacts of the manufacturing industry in the South African context.

3.1 Introduction to the wool industry in South Africa

At the turn of the century, the agricultural sector contributed 4.1% towards the national Gross Domestic Product (GDP) of South Africa [11]. Similarly, agricultural products have contributed approximately 8%, on average, for the last five years to the total exports. Of the R15 billion in revenues, generated from agricultural exports in 2000, roughly 2% were attributable to the export of wool fibres [113]. Although the component of wool in the national economy is therefore reasonably small, the industry is nevertheless seen as important as South Africa is the sixth largest producer of this product, i.e. 3 to 4 % (33 000 tonnes) of the global production [114, 115]. Also, the significance of the environmental impacts associated with wool production has been receiving attention in the South African textiles industry [111].

3.2 Goal and scope of the wool life cycle case study

3.2.1 Allocation of environmental impacts within the SA wool industry

South Africa has a wool-producing sheep population in the order of 20 million, i.e. approximately half of the human population, of which more than 10 million are located in the Western Cape, Eastern Cape and Northern Cape provinces (Table 3.1) [116]. The Nama Karoo Biome comprises the largest vegetation type in this region [31]. Less than one percent of this biome is formally conserved and this may be partially related to the high land use requirements for farming due to the low grazing capacity associated with this eco-region [116]. The rainfall in this region is also low with the bulk receiving less than 400 mm per year and the management of the natural resources, i.e. water and land (and soil erosion), has received much attention [117]. These resource constraints, amongst other factors, have resulted in the number of sheep farming activities remaining fairly constant. In the case of certain sheep breeds, some of the environmental impacts related to the farming activities should be allocated to the meat production sector. However, with Merino sheep, wool constitutes the primary product and the impacts are allocated solely to this produce.

Table 3.1: Wool sheep population in South Africa [116]

Sheep type	Year	Cape Provinces (thousands)	Total for RSA (thousands)
Merino (50% of all sheep)	1992	9 711	16 762
	2000	9 662	14 063
Other wool sheep	1992	1 375	3 763
	2000	2 354	5 970

The downstream or post-farming life cycle stages of wool production have also received considerable attention [118]. The primary environmental concerns are associated with the release of wastewater from the textile processes, and especially [114]:

- Pesticides from the washing and scouring phases.
- Halogen aromatic organic compounds (AOX) originating from the shrink-resist chlorine-based process.
- Chromium in the dyeing process.

Other ambient water quality criteria that are influenced include the Biological Oxygen Demand (BOD), Total Suspended Solids (TSS) and concentrations of oils from the wool fibres [119]. In some cases acidic waste streams are treated with lime, which necessitates waste disposal of the consequent solids. Additional environmental impacts are the result of energy requirements, and associated air emissions, for steam production and electricity supply, although these have not received much attention. Allocation of impacts within the wool production process is required between wool fibres, and noil short fibres and wool grease as by-products [118]. These by-products do not have the economic value of the wool fibres considered adequate for shrink-resist treatment, spinning and dyeing, and the allocation is therefore based on the mass ratio of the different products.

3.2.2 The purpose of the wool case study

The production of wool has an environmental bearing on all four the air, water, land and mined abiotic resource groups. The spectrum of impacts therefore makes the production of wool in South Africa a relevant screening Life Cycle Assessment (SLCA) case study to evaluate and compare the quantitative results of different LCIA methodologies.

3.2.3 The functional unit of the wool case study

The functional unit of the SLCA case study is 1 kilogram of dyed two-fold yarn wool, either for export, or for local fabric manufacture. The life cycle system to produce this functional unit is divided into two distinct processes with sub-processes:

- Sheep farming and the associated management thereof to ensure profitability, including grazing management, liquid and nutritional supplementation, disease control, shearing and classing of wool fleece, etc.
- The industrial production of wool associated with transforming the natural fibres into yarn for subsequent weaving of wool fabric, and includes the sub-processes of scouring and carbonising, top making, shrink-resist treatment, spinning and final dyeing.

Two transportation phases are required to transfer the fleece from the wool farms to the industrial processes, and to transport product streams within the industrial system, i.e. shrink-resist treated wool to the spinning mill. Auctioning of the greasy wool takes place before the wool is industrially processed.

3.2.4 Boundaries setting of the wool case study

As the case study is an SLCA, the actual use and final disposal of the dyed two-fold yarn is not included and the life cycle study is therefore a cradle-to-gate assessment of the manufacturing life cycle stages of wool in South Africa. The reason for this demarcation is the complexity of the use and end-of-life phases of wool in the South African textiles industry.

The unit processes that serve to provide input streams into the life cycle, and which are included in the boundaries of the study, are determined by the relative mass, energy and economic value of the input streams compared to the functional unit [120]. According to this Relative Mass-Energy-Economic (RMEE) method, unit processes with a mass, energy and economic ratio of less than 0.05 compared to the functional unit will contribute less than 5% of the overall environmental impacts of the life cycle system [121], i.e. a cut-off ratio of 0.05 has a mean of 99.38% of the total environmental burdens with a confidence interval of 95% (low value of 96.67%). The functional unit of this case study does not have an actual energy value. In the case of the energy comparison, the contribution of an input stream to the overall energy input of the wool life cycle system is considered, i.e. an energy ratio of less than 0.05 compared to the whole system is again used as the cut-off criteria. It must be noted that problems have been attributed to cut-off procedures in life cycle studies [122]. However, for the simplified case study, the RMEE method is assumed adequate to determine the most important processes that contribute to the impacts of the overall system.

In terms of the farming activities, the environmental burdens of shearing with mechanical hand pieces, which is still the most common practice, and classing are not large and are not taken into account in this case study. Similarly, the impacts associated with the auctioning of the wool have explicitly not been considered.

3.3 Inventory of the wool life cycle case study

3.3.1 Process diagram

A simplified process diagram of the wool life cycle system is shown in Figure 3.1.

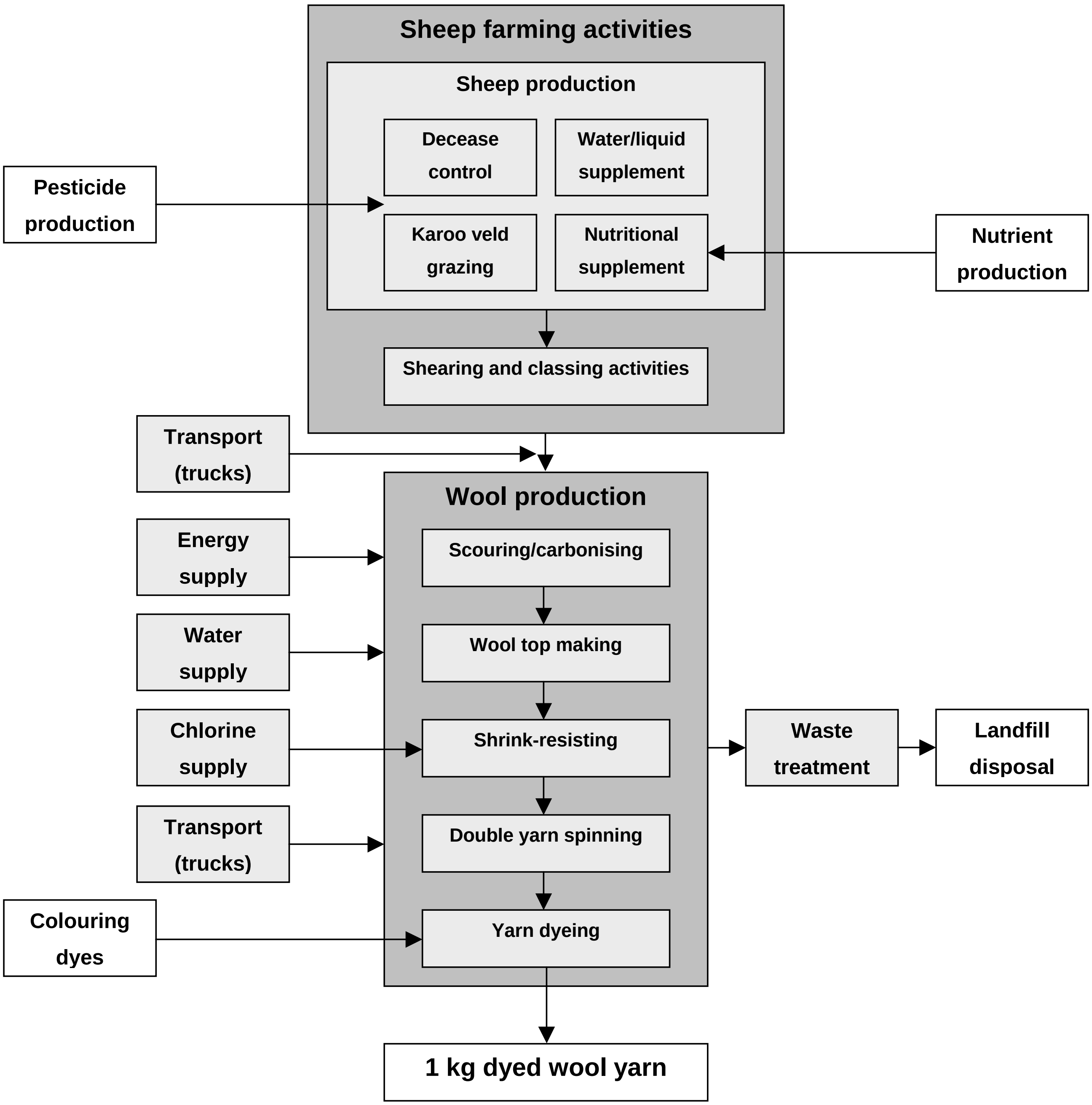

Figure 3.1: The evaluated wool life cycle system in South Africa

Shaded areas: included in the boundaries of the life cycle system

Non-shaded areas: not included in the boundaries of the life cycle system

3.3.2 Data gathering

3.3.2.1 Sheep farming

Data with regards to sheep farming practices were mainly obtained from two sources:

- South African literature, with particular emphasis on the type of ecosystems associated with the region where the farming is assumed to take place.
- International publications where South African data could not be obtained.

3.3.2.2 Wool production

The following sources were used to determine the impacts associated with industrial wool production:

- Personal interviews, held with the Division of Manufacturing and Materials Technology of the CSIR and South African wool industries in the Western and Eastern Cape provinces.
- International literature and reference material.

3.3.3 Data quality

Data quality can be analysed in terms of validity, i.e. representative of the life cycle system, and reliability, i.e. the completeness, variability and uncertainty of the data [123]. Although the data is representative of the life cycle system, reliability is problematic. Sheep farming practices vary according to the specific eco-regions of South Africa, i.e. the resource-use for wool produce is dependent on the regional climate conditions. Also, a comprehensive survey of farming methods is required to ensure the completeness of inventory data.

Furthermore, the information supplied by South African industries was incomplete and highly variable. The environmental practices of the local industry probably differ from those in developed countries to some degree, with a consequent high uncertainty where data from international publications was used. However, for the purposes of the SLCA case study, the data quality is adequate to quantitatively evaluate and compare the different LCIA models.

3.3.3.1 Sheep farming

The case study assumes that wool farming takes place in the eastern parts of the Karooveld region of South Africa in what is typically known as the Little Karoo. This region falls within the Eastern Cape Province, which contributes 26% of the total wool production of South Africa (Figure 3.2) [116].

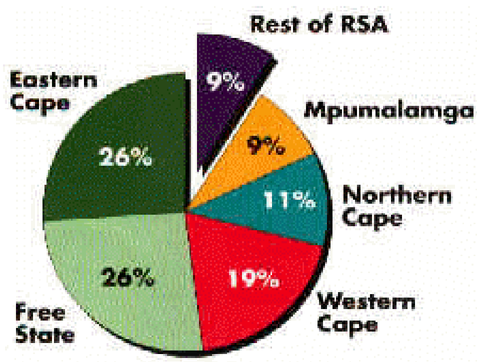

Figure 3.2: Wool production by region in South Africa [116]

The area where wool sheep farming is assumed to take place is shown in Figure 3.3 [124]. The case study area mainly falls within the N and Q primary water catchments as defined by the South African Department of Water Affairs and Forestry and is characterised by lower and mixed Nama Karoo vegetation types [31]. The grazing capacity of the area is between 14 and 24 hectares per Large Stock Unit (LSU) per year [117].

The LSU equivalent values for wool sheep, e.g. Merino, are shown in Table 3.2 [125]. The LSU equivalent value for a wether is assumed as an average for a farm in the chosen area, and the maximum grazing capacity therefore allows 2.85 hectares (28 500 m^2) per wool sheep. This translates to a medium grazing burden for these Karooveld types [126].

Figure 3.3: Area assumed where wool farming takes place [adapted from 124]

Table 3.2: Large Stock Unit (LSU) equivalence for wool sheep [125]

Sex and state	Weight	LSU equivalence
Lamb, weaned	20 kg	0.10
Ewe, 6 tooth, dry	47 kg	0.14
Wether, 6 tooth	50 kg	0.15
Ram, 6 tooth	64 kg	0.19

A 50 kg Merino wether annually produces approximately 4 kg of fleece, of which 3 kg constitutes wool fibres and the remaining being wax, suint, dirt and other materials [127]. To achieve a maximum rate of wool growth, a Merino sheep must absorb 120 to 150 g of protein per day or approximately 50 kg per year and roughly 1600 MJ of energy per year [128]. This is equal to 117 g of protein per kg of dry matter (DM) per day for Merino sheep, while Karooveld types typically contains 97 to 112 g protein per kg DM depending on seasonal changes. A nutritional supplement is therefore typically required and possible rations have been suggested for South African production during dry periods, which is shown in Table 3.3 [129]. The minimum DM intake for a 50 kg sheep is 1.03 kg per day [128]. It is assumed that the 2.85 hectares of Karooveld can produce this mass. An additional 45 kg of DM per sheep per year is subsequently required and the content of ration 2 (content but not actual mass) in Table 3.3 is assumed, i.e. approximately 22.5 kg of maize and lucerne each is required per sheep per year. Furthermore, sheep require in the order of 3 to 6 kg of water per kg DM for the temperatures experienced in the case study region [128], which is equal to a minimum of 1.26 tonnes of water per sheep per year. It is assumed that this water is obtained from groundwater reserves.

Table 3.3: Weekly nutritional supplement for a 50 kg wether sheep (dry periods) [129]

Ration	Mass (kg)	Food content (%)		
		Maize	Lucerne	Grain hay
1	5.3	75	25	0
2	6.1	50	50	0
3	7.3	25	75	0
4	7.8	30	40	30

To ensure the health of the sheep flock, pesticides and other medicinal products are used. The cost of administering these products is in the order of 83% of the nutrient supplement costs [130]. However, it is variable and dependent on the diseases that may be contracted by a flock from time to time [130, 131]. For this case study it is assumed that pesticides are administered on the flock, resulting in a final wool clip concentration similar to that measured on average Australian wool [132]:

- Synthetic pyrethroid (mainly cypermethrin) - 2.0 mg/kg
- Cyromazine - 5.1 mg/kg
- Dicyclanil - 0.1 mg/kg
- Diflubenzuron - 2.9 mg/kg
- Triflumuron - 9.0 mg/kg

Due to the administering techniques of the pesticides (dipping, spraying, etc.), as well as ambient degradation of the chemical compounds on the sheep, the final concentrations are probably less than 1% of the initial dosage, i.e. the total pesticides usage is in the order of 2 g/kg fleece per year. For the case study it is taken that 50% of the total administered pesticides adheres to the wool with the remainder discharged on the farm, of which 20% is released into natural water systems and the balance destroyed by natural processes, i.e. sunlight.

A further important step in the farming activity is the shearing and classing of the wool clip, typically performed half-yearly [133]. This step accounts for up to 15 % of the total costs associated with wool farming [132]. Some 60% of the shearing and classing costs are related to labour and the remaining 40% is needed for the maintenance of infrastructure to support these operations. It is therefore imperative that these operations be managed efficiently. However, as stipulated in Section 3.2.4, the environmental burdens of these activities are not considered in the case study as those burdens are assumed to be small in relation to the other farming activities.

3.3.3.2 Wool production

Two processes are used for the manufacture of wool, i.e. worsted and woollen processes. The South African textiles industry follows the worsted process. The sub-processes or unit processes operate separately with storage in between. For transportation requirements, European databases [134] have been updated with South African measurements [135]. Energy is required by each of the unit processes in the form of steam and electricity. The latter is directly obtained from the South African utility (Eskom) network with the following contribution of generation methods [136]:

- Thermal (coal) processes - 88.6%
- Hydropower - 0.7%
- Nuclear power - 6.7%
- Imported from outside South Africa - 2.7%
- Pump storage or potential electricity - 1.3%

The life cycle inventory of the thermal generation method is based on European databases [134] and updated with company-specific information [136]. The other generation methods are based on European data as well [134]. The steam that is required by the unit processes is produced on site at the manufacturing facility. Based on information from the textiles sector [131] and performance measurements in the textiles industry [137], it is assumed that typical chain grate boilers are used; two for the scouring, top making and shrink proofing with 6 tonne/hr capacities and one for the spinning and dyeing unit processes with a 3 tonne/hr capacity. These are on separate sites. Table 3.4 shows the operational data for a measured (4740 kg/hr) boiler [137].

Table 3.4: Measurement data of a typical chain grate boiler in South Africa [137]

Input	Value	Unit	Output	Value	Unit
Coal	570	kg/hr	Ash	95	kg/hr
			Dust (air)*	1.7	kg/hr
			NO_x (as NO_2)**	10	g/hr
Water	2030	kg/hr	CO_2	1414	kg
			SO_2	270	ppm
			C_xH_y**	23	g/hr

* Pro rata calculation from separate measurements performed on larger boilers

** Determined from European databases of similar boiler processes

The case study assumes that a scouring, top making and shrink proofing facility is situated in the town of Uitenhage in the Eastern Cape Province, and a spinning and dyeing facility in Cape Town in the Western Cape Province. Freshwater of drinking quality is obtained directly from the towns' supplies.

Scouring and carbonising

Wool is purchased through an auctioning process and is based on the pure wool content. Evaluating the content has been standardised (IWTO-19-76) with typical compositions being as follows [114]:

- Pure wool - 55%
- Wool grease - 10%
- Wool suint - 4%
- Soil and vegetable matter - 19%
- Moisture - 12%

To remove the majority of impurities, the wool is scoured through an emulsion process. It entails washing the wool in warm water containing detergent, which is made alkaline (pH greater than 9) with sodium carbonate (Na_2CO_3) [132]. The washing takes place in a series of four baths or troughs with mechanical raking (four 5 kWh motors), totalling 5 000 litres; the first is maintained at 60ºC; the second at 50ºC; and the third at 40ºC, with the concentrations of detergent and sodium carbonate decreasing with subsequent troughs [131, 138]. The total mass of detergents and sodium carbonate is assumed to be less than 1% of the overall mass production rate [131, 139]. Scouring does not remove the entire vegetable fault, particularly burr, and further carbonising is required for certain wool types that contain excessive amounts of vegetable matter. This process involves the treatment of the scoured wool with diluted sulphuric acid (pH of 2) [131, 139].

The scouring and carbonising process produces between 300 and 700 kg clean wool per hour of wool (0.5% wool grease quality), and is dried afterwards with steam heat dryers at 100ºC [131, 138, 139]. The overall process requires 9 litres of water (drinking quality) per kilogram of greasy wool. The process generates more than 6 litres wastewater per kilogram of wool [114], which is centrifuged (20 kWh) to remove the greases before it is mixed with acidic effluents from upstream processes and treated in evaporation ponds extending over 2 hectares for annual treatment [131, 139]. This translates to an evaporation rate of approximately 1 metre of water per year. The wastewater typically consists of greases (191 g/kg of wool) and substances that impact on water quality in terms of BOD (292 g/kg of wool), TSS (197 g/kg of wool) and pesticides (less than 6.5 % of the pesticides typically adhere to the wool after the washing process) [119, 140].

With respect to waste streams, the evaporation ponds and their boundaries with nature have been included in the case study. No site-specific measurement data is available and it is estimated that 10% of all pollutants entering the ponds is released to the groundwater reserves. The transportation of solids from the treatment facility to a local landfill site has been included in the boundaries of the study [141].

Top making

Carding to form slivers disentangles the scoured and carbonised wool. Through a process of combing and stretching, the slivers are transformed into wool tops with a linear density of 14 to 24 g per metre of wool [114]. The top making process requires the addition of lubricants and antistatic agents in the order of 1% of the fibre mass, and 0.5 kWh energy per kilogram of wool. The production rate is 100 kg per hour and between 5 and 10% is lost through noil by-products (short fibres). A burr waste stream in the order of 0.05% of the final product is also produced through this unit process.

Shrink-resist treatment

Wool is shrink-resist treated for the consumer phase use of wool, e.g. for machine-washable apparel articles. This unit process consists of four 3000-litre baths in series and a production rate of 360 kg/hr [131, 139]:

- Chlorination with a 2% chlorine (Cl_2) solution at room temperature.
- Neutralisation and rinsing with a sodium sulfite (Na_2SO_3) solution (< 0.5%) at 40ºC.
- Rinsing with fresh water at 40ºC.
- Treatment with a 2% cationic polymer or resin, i.e. epichlorohydrine, at 40ºC.

The wool is also treated with a cationic softener and lubricant (1% of wool mass) to facilitate further processing before being dried and cured in a steam-driven oven at 120ºC [142]. It is assumed that five electric motors of 5 kWh each are required to drive the process. The treatment baths require 7 litres of freshwater per kilogram of wool processed. Shrink-resistance generates more than 6 litres of wastewater per kilogram of wool, with a pH of 2 and halogen aromatic organic (AOX) substances with a concentration of 2 mg/kg effluent and mixed with the scouring and carbonising waste stream for treatment in the evaporation ponds [131, 139].

Yarn spinning

The case study assumes that spinning the wool comprises the production of two-fold yarn at a rate of 206 kg/hr [131, 138]. A steam autoclave is required for the yarn setting with 7 kWh and 15 kWh motors required for winding and twisting separately. Approximately 7% of the product is lost through fibre breakage [142]. Lubricants and antistatic agents are required in the order of 1% of the yarn produced.

Yarn dyeing

Wool is dyed in an aqueous solution, which is maintained at 100ºC with steam [131, 138]. Freshwater is used at a rate of 30 litres per kilogram of wool yarn. During package dyeing the pH level is kept at 3 throughout the operation with the addition of acetic acid (CH_3COOH). Chrome dyes (less than 0.5% by mass) are most often used, although premetalised, acid and reactive dyes are also used in South Africa. The process produces a waste stream of 25 litres per kilogram of wool, typically consisting of 27 g/kg BOD and 1.33 g/kg chrome [119]. The unit process incorporates recycling procedures for wastewater to reduce these pollutants as far as possible. For a direct discharge into surface water from dyeing processes an international standard has been specified for the BOD (50 mg/l) and Cr (0.5 mg/l) content [119]. It is assumed that the wastewater concentrations from the South African processes are higher by a factor of 10. The overall production rate of this unit process is in the order of 125 kg/hr.

3.3.3.3 Post-production life cycle stages

Although specifically excluded from the boundaries of the case study, the possible post-manufacturing life cycle stages of the functional unit in a South African context should be noted for an extensive future study:

- Loom stating and weaving of the two-fold dyed yarn.
- Wool fabric and clothing manufacturing.

- Wholesalers and retail supply of finished clothing products.
- Consumer usage and final use of the fabric, e.g. as rags.
- Final disposal of the material to municipal landfill sites.

3.3.4 Inventory data

The values of the unit processes of sections 3.3.3.1 and 3.3.3.2 have been altered accordingly to produce the functional unit and is summarised in Table 3.5, i.e. the input and output parameters of the unit processes are determined by calculating from the gate (bottom of the table) to the cradle farming activities (top of the table).

3.3.5 Omitted data

The following unit processes have been omitted from the life cycle system and the completeness of the inventory dataset is thereby reduced (see Figure 3.1):

- Pesticide production. The costs of pesticides are significant in terms of the RMEE method and the supply thereof should be included in the study, but little information is available for these types of pesticides in South Africa. However, the use and emission of these substances is included in the case study.
- Nutritional supplement production. The required costs and masses of food supplements are significant. The environmental burdens associated with these unit processes are not considered as important as those directly related to the wool system, but should be included in the future expansion of a detailed wool life cycle study.
- Chemical materials. The RMEE method excludes the required materials (except chlorine and epichlorohydrine) from the study, e.g. dyes, detergents, acids, etc., but the true environmental impacts associated with the production of these materials should be considered in a detailed study.
- Water supply. The environmental burdens related to the supply of drinking quality water for processing are excluded from the case study as municipal-specific information is required for a detailed study.

Table 3.5: Life cycle inventory constituents considered in the case study

Stage	Sub-stage	Flow	Constituent	Value	Unit	Comments
Wool farming		Inputs	Karoo veld (land)	10247	m^2	28500 m^2 per sheep producing 4 kg fleece
			Water (drinking)	453	kg	1.26 t/yr/sheep sheared twice annually for 2 kg
			Maize supplement[a]	8.09	kg	22.5 kg/yr/sheep producing 4 kg fleece
			Lucerne supplement[a]	8.09	kg	22.5 kg/yr/sheep producing 4 kg fleece
			Pesticides[a]	3	g	2 g/kg fleece
		Output	Greasy wool	1.97	kg	No weight change during transportation
			Pesticides (water and soil emissions)	1	g	10 % of administered pesticides emitted to water and 40 % to soil; 10 % on final fleece
Transportation		Input	Long distance trucks	0.39	tkm	200 km from the little karoo to Uitenhage
		Output	Greasy wool[b]	1.97	kg	40 % loss during scouring and carbonising
Wool production	Scouring	Inputs	Electricity	0.2	MJ	40 kWh at 80% efficiency for 500 kg/hr
			Steam	12.25	kg	Allocation based on production rate
			Freshwater	12.94	kg	9 l/kg of greasy wool
			Detergent	9	g	1 % of unit process product
			Na_2CO_3	9	g	1 % of unit process product
			H_2SO_4	1	g	1250 l bath maintained at a pH of 2
		Outputs	Cleaned wool[c]	1.18	kg	7.5 % loss during top making (noil by-product)
			Wastewater effluent	5.17	kg	6 l/kg of unit process product (for treatment)
			BOD	0.25	kg	292 g/kg of unit process product
			TSS	0.17	kg	197 g/kg of unit process product
			Greases[b]	0.23	kg	191 g/kg of unit process product
			Detergent	4	g	Effluent to freshwater feed ratio
			Na_2CO_3	4	g	Effluent to freshwater feed ratio
			Pesticides	14	mg	6.5 % on clean wool, 50 % in grease
	Top making	Inputs	Electricity	0.02	MJ	0.5 kWh at 80 % efficiency for 100 kg/hr
			Steam	4.98	kg	Allocation based on production rate
			Lubricants/antistatic	0.01	kg	1% of main unit process product
		Outputs	Wool tops	1.09	kg	1 % product loss during shrink-resist treating
			Waste stream	5	g	0.05 % of unit process product (no treatment)
			Noil by-products[c]	0.09	kg	7.5 % of processed wool

a The impacts of producing these input streams are omitted from the case study

b Impacts of upstream processes are allocated separately for greases

c Impacts of upstream processes are allocated separately for noil by-product

Table 3.5 (continued)

			Constituent	Value	Unit	Comments
Wool production	Shrink-resist treating	Inputs	Electricity	0.22	MJ	25 kWh at 80 % efficiency for 360 kg/hr
			Steam	5.33	kg	Allocation based on production rate
			Freshwater	7.63	kg	7 l/kg of processed wool
			Cl_2	0.18	kg	2 % solution for 3000 l
			Na_2SO_3	0.045	kg	0.5 % solution for 3000 l
			Epichlorohydrine	0.18	kg	2 % solution for 3000 l
			Softener	0.01	kg	1 % of unit process product
		Outputs	Shrink-resisted wool	1.08	kg	No weight change during transportation
			Wastewater effluent	7.63	kg	7 l/kg wool processed
			HCl	3	g	pH of effluent is 2 (to waste treatment)
			AOX	15	mg	2 mg/kg effluent (to waste treatment)
Transportation		Input	Long distance trucks	0.81	tkm	750 km from Uitenhage to Cape Town
		Output	Shrink proofed wool	1.08	kg	7 % product lost in the spinning process
Wool production	Spinning	Inputs	Electricity	0.308	MJ	22 kWh at 80 % efficiency for 206 kg/hr
			Steam	7.16	kg	Allocation based on production rate
			Lubricants	0.01	kg	1 % of unit process product
		Output	Two-fold yarn	1	kg	No weight gaining during dyeing
	Dyeing	Inputs	Freshwater	30	kg	30 l/kg of wool produced
			Steam	4.46	kg	Allocation based on production rate
			Chrome dyes	5	g	0.05 % by mass of wool produced
			CH_3COOH	3	g	45 l at a pH of 3 with 98% CH_3COOH
		Outputs	Dyed two-fold yarn	1	kg	Ready for manufacturing or export
			Wastewater effluent	25	kg	25 l/kg of wool produced
			BOD	12.5	g	0.5 g/kg of effluent
			Cr	125	mg	5 mg/kg of effluent

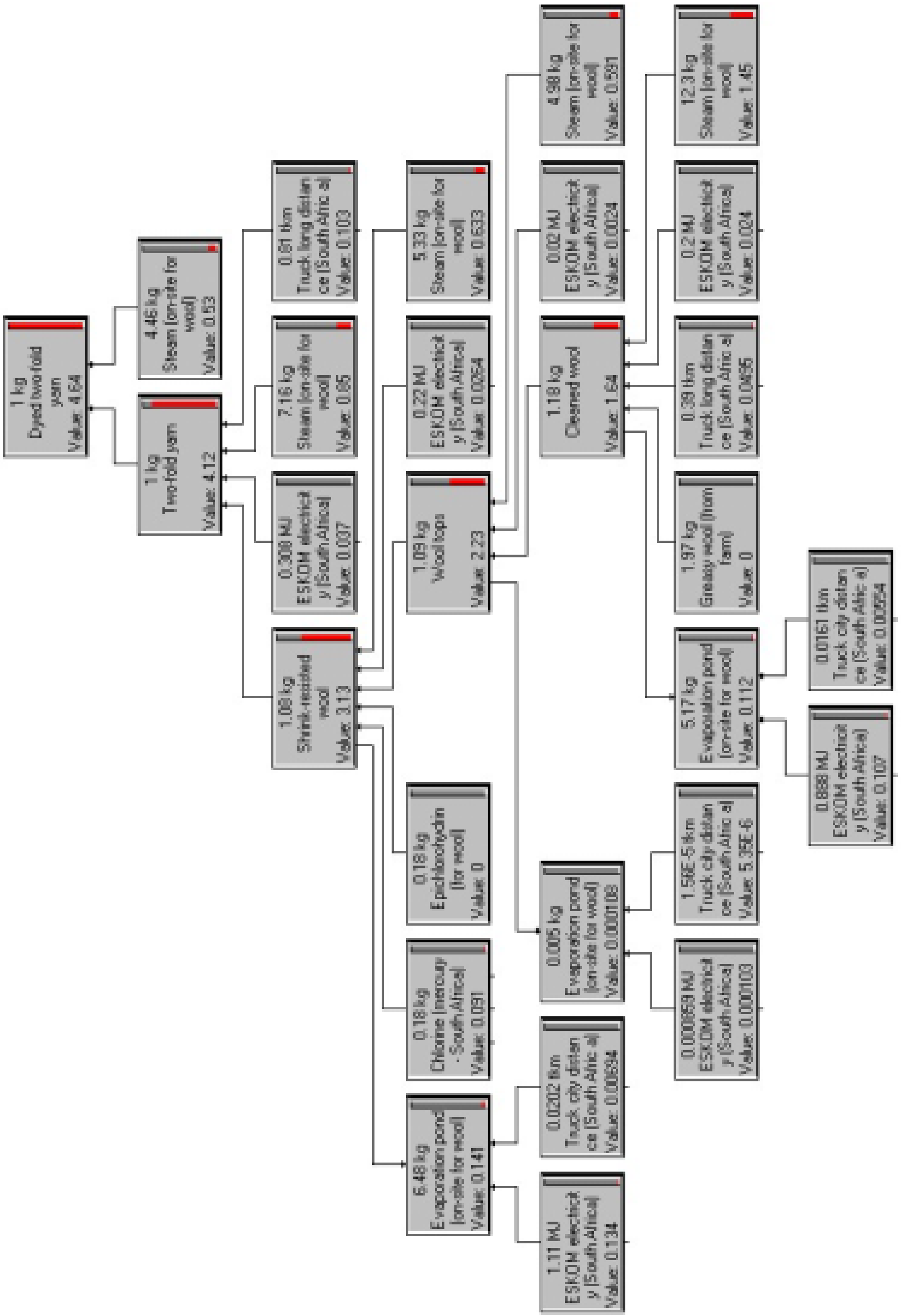

Figure 3.4: System tree to produce 1 kg of dyed two-fold yarn to be evaluated

- Solid landfill site operation. The local authorities of South Africa differ when the solid waste from wool production is classified in terms of the national regulations [141]. Also, the impacts associated with the final disposal of the solid waste are dependent on the type of landfill site specified by the local authorities. Due to these uncertainties the landfill site operations and its related environmental burdens have been excluded from the case study. Furthermore, compared with the direct process releases to the ambient environment, the release of pollutants from properly managed disposal sites are presumed to be considerably less.
- Impacts associated with the general operation of the farm and facilities' infrastructure, i.e. air conditioning, lighting, on-site transportation and fuel, labour impacts, etc. have not been included in the simplified life cycle inventory.

The system tree with the included unit processes is shown in Figure 3.4. The figure also shows the cumulative use of coal to produce the functional unit.

The wool life cycle system has been compiled with the SimaPro LCA software package on the CSIR server [143]. The package can be used to evaluate and compare LCIA results of life cycle systems [134].

3.4 Life Cycle Impact Analyses (LCIA) results of the wool life cycle case study

The most important Life Cycle Inventory (LCI) constituents that describe the interaction between the unit processes included in the wool manufacturing life cycle system and nature are given in the LCI profile of Table 3.6, with which the different LCIA procedures can be analysed quantitatively.

Table 3.6: Life Cycle Inventory (LCI) profile of the dyed two-fold yarn system

Inventory constituent	Resource group	Value[a]	Unit	Inventory constituent	Resource group	Value[a]	Unit
coal	Mined	4.62672	kg	NO_x (as NO_2)	Air	7.98	g
crude oil	Mined	74.01	g	SO_2	Air	52.2	g
iron ore	Mined	2.53	g	V	Air	2.77	mg
lignite	Mined	6.07	g	xylene	Air	14.2	mg
methane	Mined	3.66	g	AOX	Water	1.37	mg
rock salt	Mined	121	g	As	Water	2.94	mg
As	Air	109	µg	BOD	Water	35.3	g
Ba	Air	647	µg	Ca	Water	1.3	g
Be	Air	6.58	µg	COD	Water	8.49	mg
CH_4	Air	6.36	g	Cr	Water	140	mg
Cl_2	Air	1.71	mg	C_xH_y	Water	17.9	mg
CO	Air	2.19	g	HCl	Water	273	mg
CO_2	Air	11.2	kg	Ni	Water	7.35	mg
Co	Air	31.2	µg	N-total	Water	38	mg
Cr	Air	258	µg	pesticides	Water	200	mg
Cu	Air	381	µg	PO_4^{3-}	Water	87.2	mg
C_xH_y	Air	512	mg	SO_4^{2-}	Water	6.5	g
dust/particulates	Air	12.804	g	suspended solids	Water	15.5	g
HALON-1301	Air	3.56	µg	water (extracted)	Water	519.4	kg
Hg	Air	271	µg	ash	Land	791	g
NH_3	Air	10.5	mg	waste (inert)	Land	1060	g
Ni	Air	711	µg	pesticides	Land	800	mg
NMVOC (other)	Air	1.672	g	land occupied[b]	Land	10250	m^2.a

3.4.1 CML procedure results

The characterisation results of the CML methodology, using the wool life cycle system (Table 3.6), are shown in Figure 3.5. The unit processes within the direct production line of wool that contribute to the impact categories of the CML procedure are the farming (land-use and ecotoxicity) and wool dyeing (ecotoxicity) processes. Ecotoxicity is the result of chrome and pesticide emissions to the surface water resources. Except for these two categories, the category impacts are primarily the result of supporting unit processes, i.e. steam production, electricity generation, fuel production and transport, and the manufacture of chlorine.

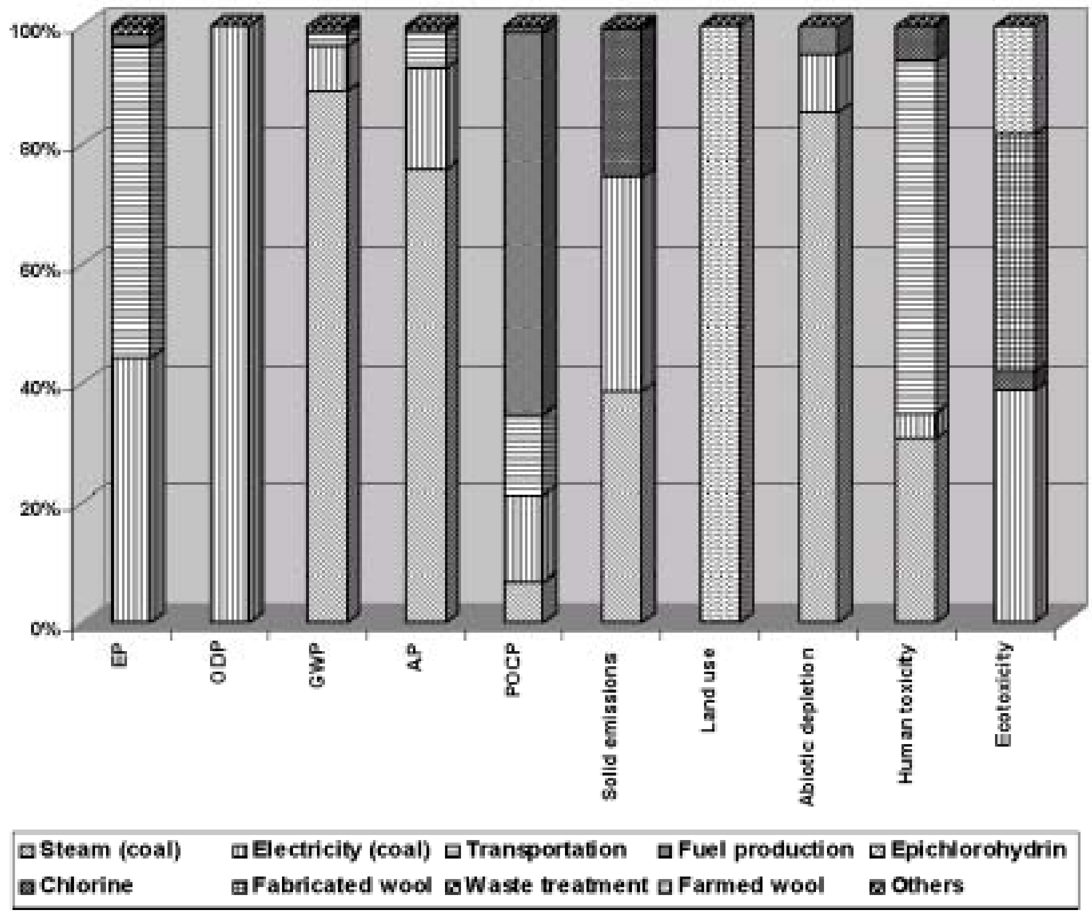

Figure 3.5: Characterisation results of the CML procedure

Electricity generation contributes to the largest number of the CML categories. This is attributable to the comprehensive European inventory databases on which this unit process is based [136, 143], i.e. the extensive list of inventory data is represented in the CML LCIA database.

The normalisation results of the CML methodology are shown in Figure 3.6. The results shown in the figure are based on actual or calculated world inventory data of CML. Using the world data indicates that land-use is the most important environmental category according to the CML procedure. As discussed in Chapter 2, no weighting mechanism has been proposed through the CML procedure.

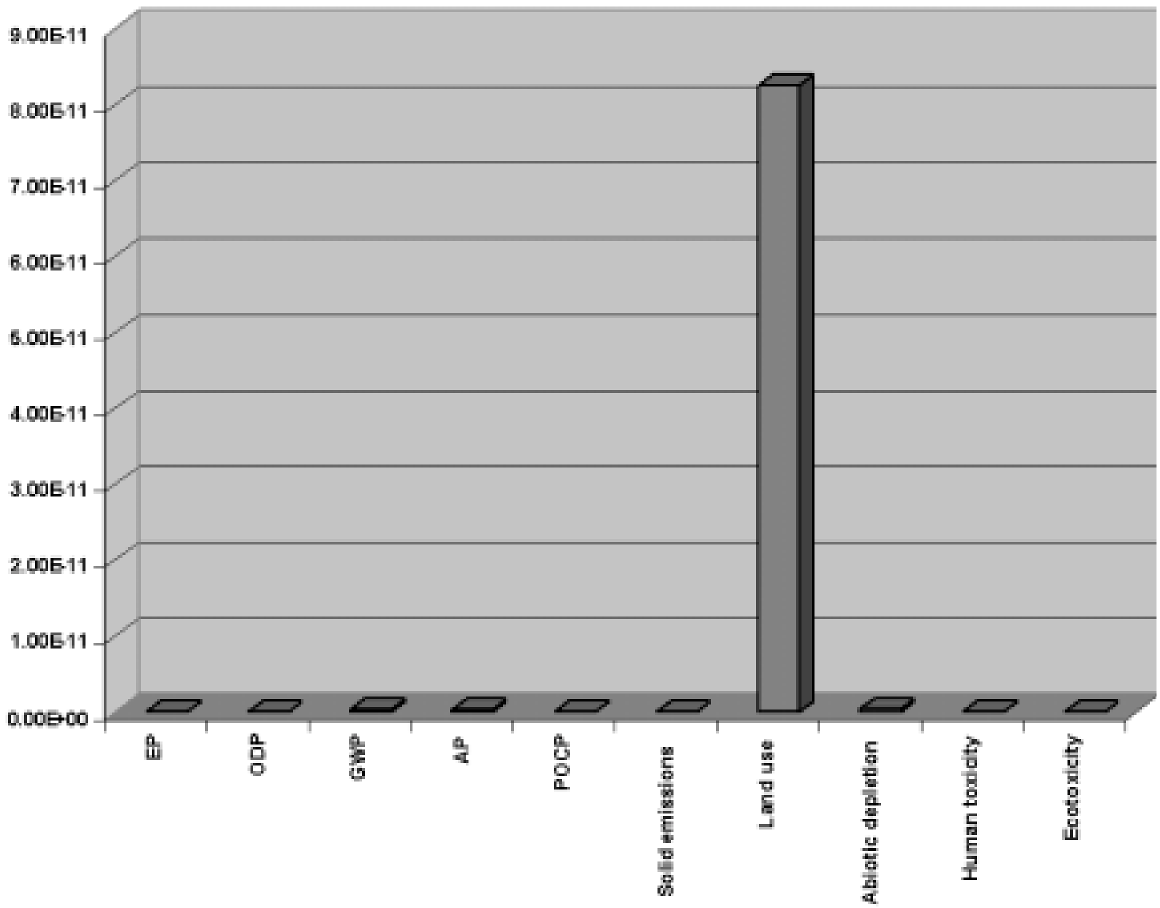

Figure 3.6: Normalisation results of the CML procedure

3.4.2 Ecopoints procedure results

The more detailed classified categories of the Ecopoints methodology with associated impact results are shown in Figure 3.7. Four of the thirty categories are not influenced through the wool inventory. The wool production is again shown to have an impact due to chrome emissions to water, but this method shows that farming only has an impact in terms of pesticide releases to soil. With respect to the number of impacted categories, electricity is again the most important contributor, but steam, transport and chlorine production (mercury emissions) are significant processes for some of the categories.

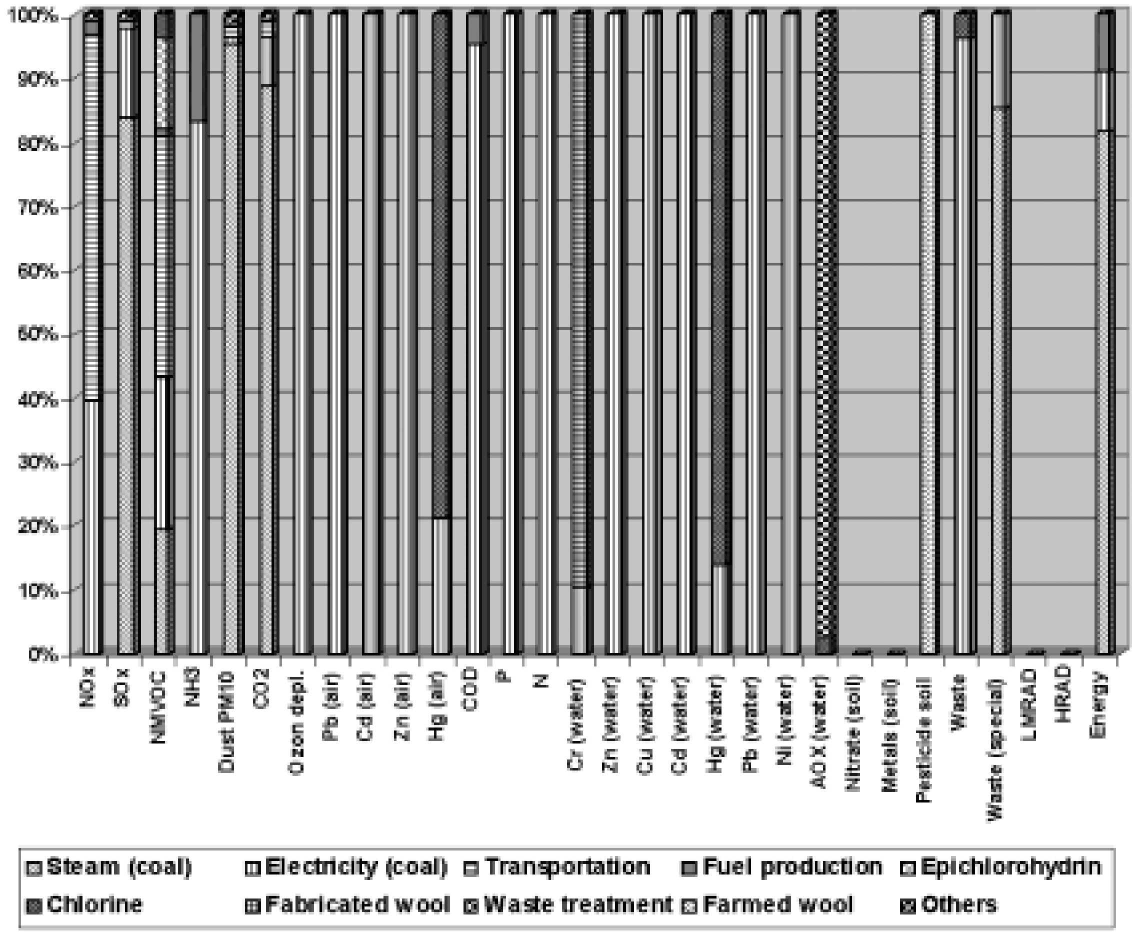

Figure 3.7: Characterisation results of the Ecopoints procedure

The Ecopoints normalisation procedure utilises Switzerland's emission and energy use data. The results are shown in Figure 3.8. The normalisation procedure shows waste, and specifically the ash generated by the electricity and steam processes, to be the most important category. Other emissions of significance are sulphur dioxide, particulates, carbon dioxide, chrome to water, and pesticides to soil.

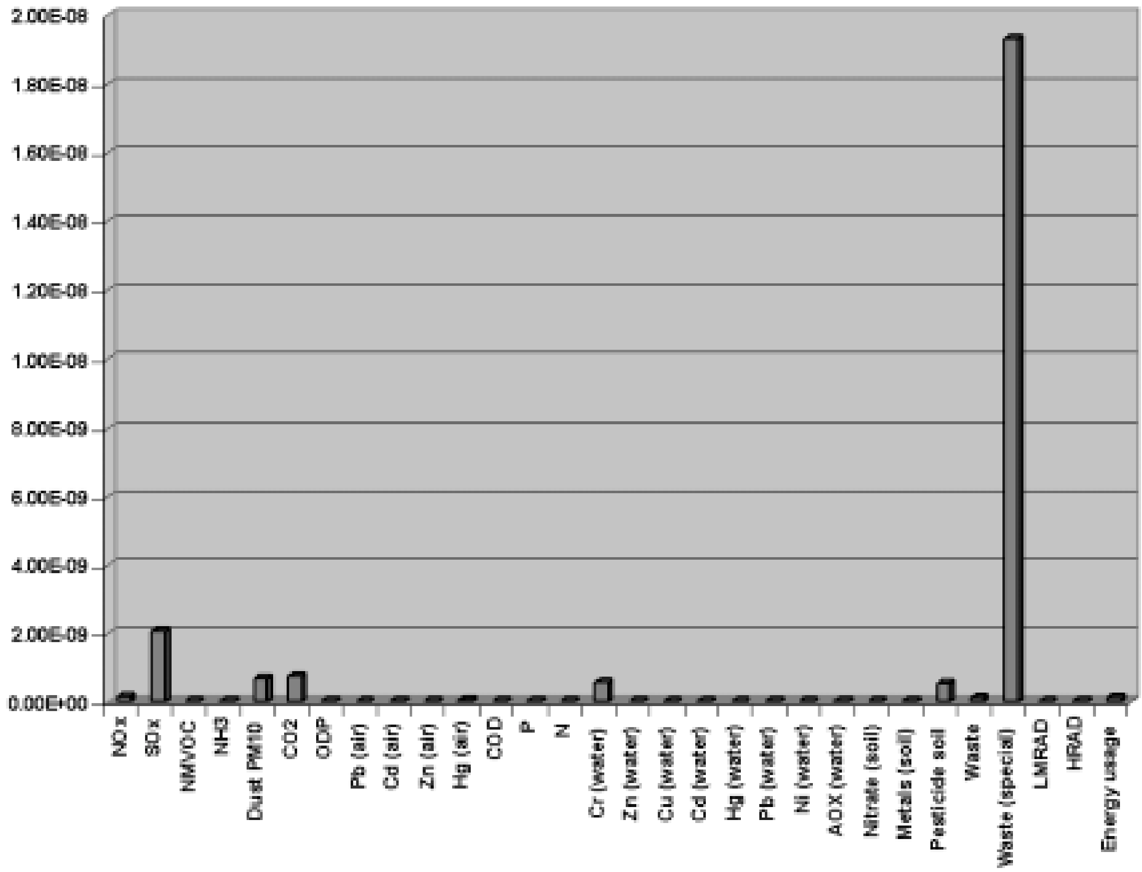

Figure 3.8: Normalisation results of the Ecopoints procedure

The results of the normalisation are emphasised through the distance-to-target weighting procedure of Ecopoints (Figure 3.9), with two exceptions. Chrome emissions to water can be disregarded, but the emissions of nitrogen oxide compounds from electricity and transport are important in the overall wool inventory.

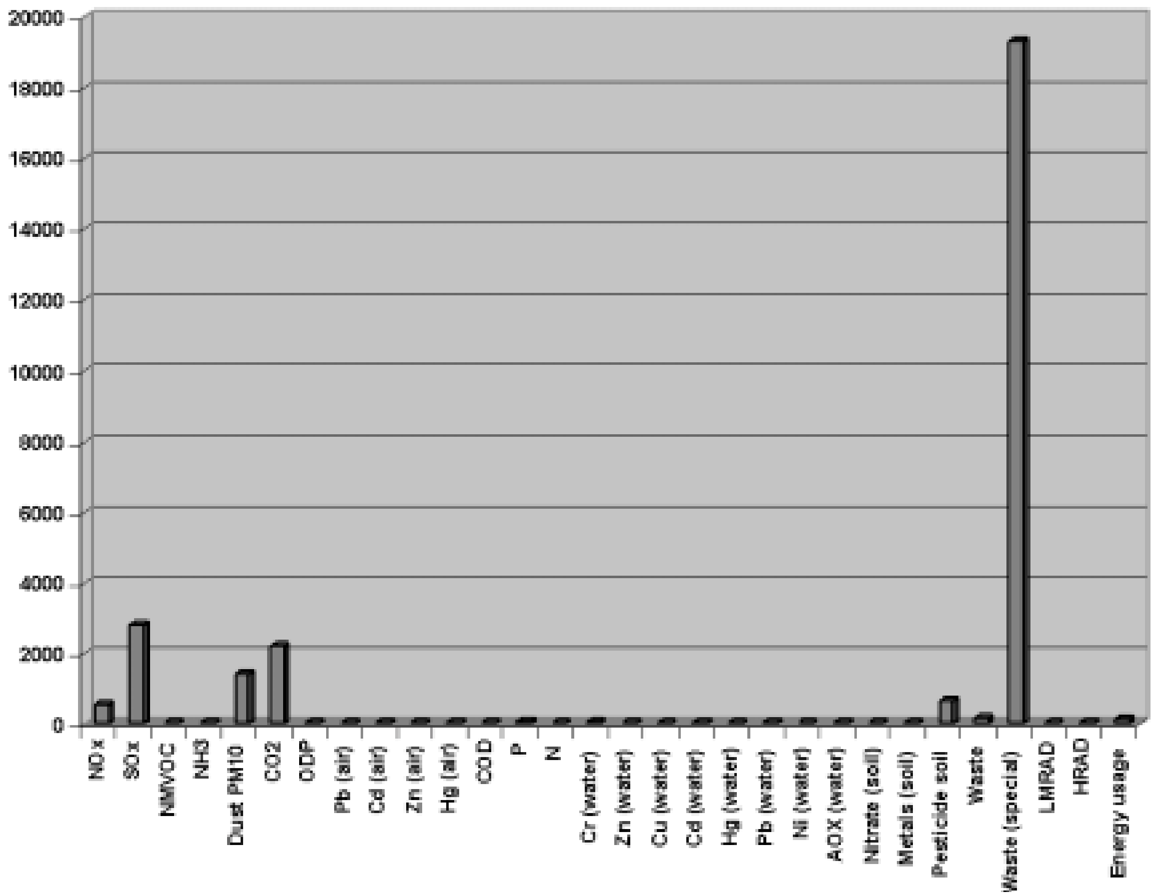

Figure 3.9: Weighting results of the Ecopoints procedure

3.4.3 Eco-indicator 95 procedure results

The characterisation step of the Eco-indicator 95 methodology (Figure 3.10) shows results similar to that of the Ecopoints procedure. The number of categories has been reduced through the grouping and incorporation of some of the Ecopoints categories into larger categories, e.g. heavy metals. However, the modelling procedure used by the Eco-indicator 95 method during characterisation shows certain deviations from the Ecopoints results. As an example, Eco-indicator 95 does not highlight the impacts of chlorine production in the heavy metals category. However, the relative contributions of unit processes to the other categories are comparable.

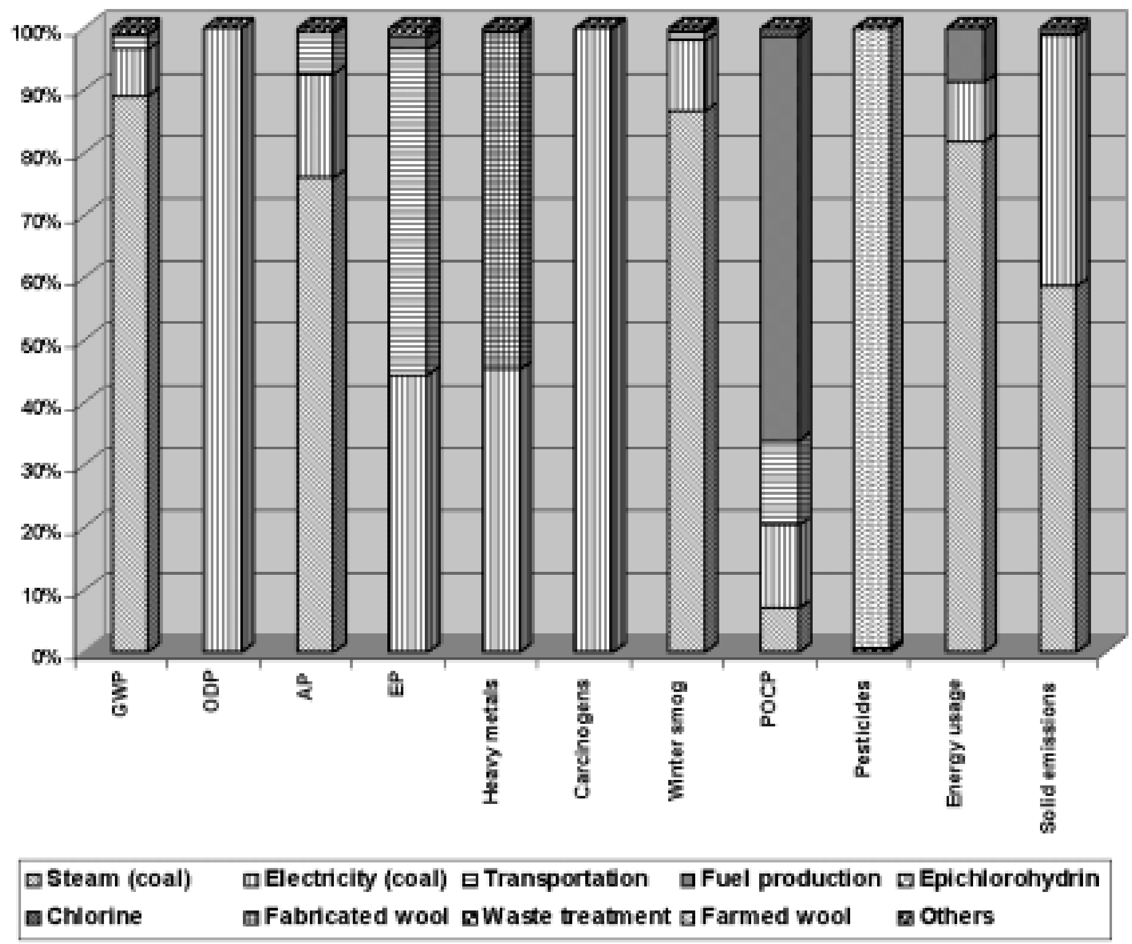

Figure 3.10: Characterisation results of the Eco-indicator 95 procedure

The normalisation step of the Eco-indicator 95 procedure (Figure 3.11) provides results dissimilar to those of the Ecopoints procedure. This is due to the normalisation data used, i.e. Western Europe as opposed to Switzerland only. Where country-specific information could not be obtained for certain emissions, the relative energy usage was used to estimate emissions. The relative GDP is also an option, but was not used for the case study. According to the normalisation step, the most important inventory data (in order) are carbon dioxide, heavy metals, particulates, energy usage, sulphur dioxide, pesticides, organics and nitrogen oxide compounds.

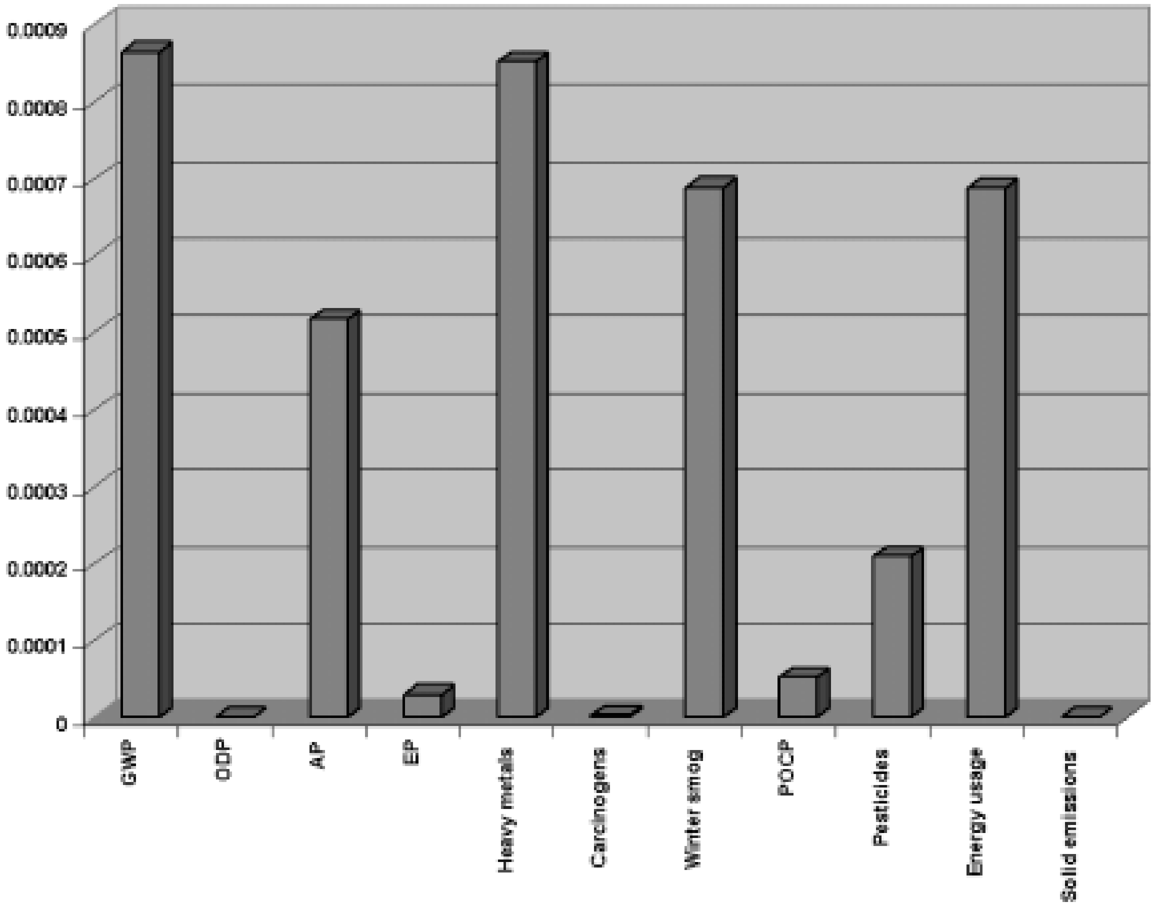

Figure 3.11: Normalisation results of the Eco-indicator 95 procedure

The distance-to-target factors used by the Eco-indicator 95 procedure in the weighting step (Figure 3.12), alters the importance of the categories and the inventory data that adds to these, i.e. pesticides, sulphur dioxide, heavy metals, particulates, carbon dioxide, nitrogen oxide compounds and organics. No weighting value is placed on energy resources used, which results in the exclusion of this category.

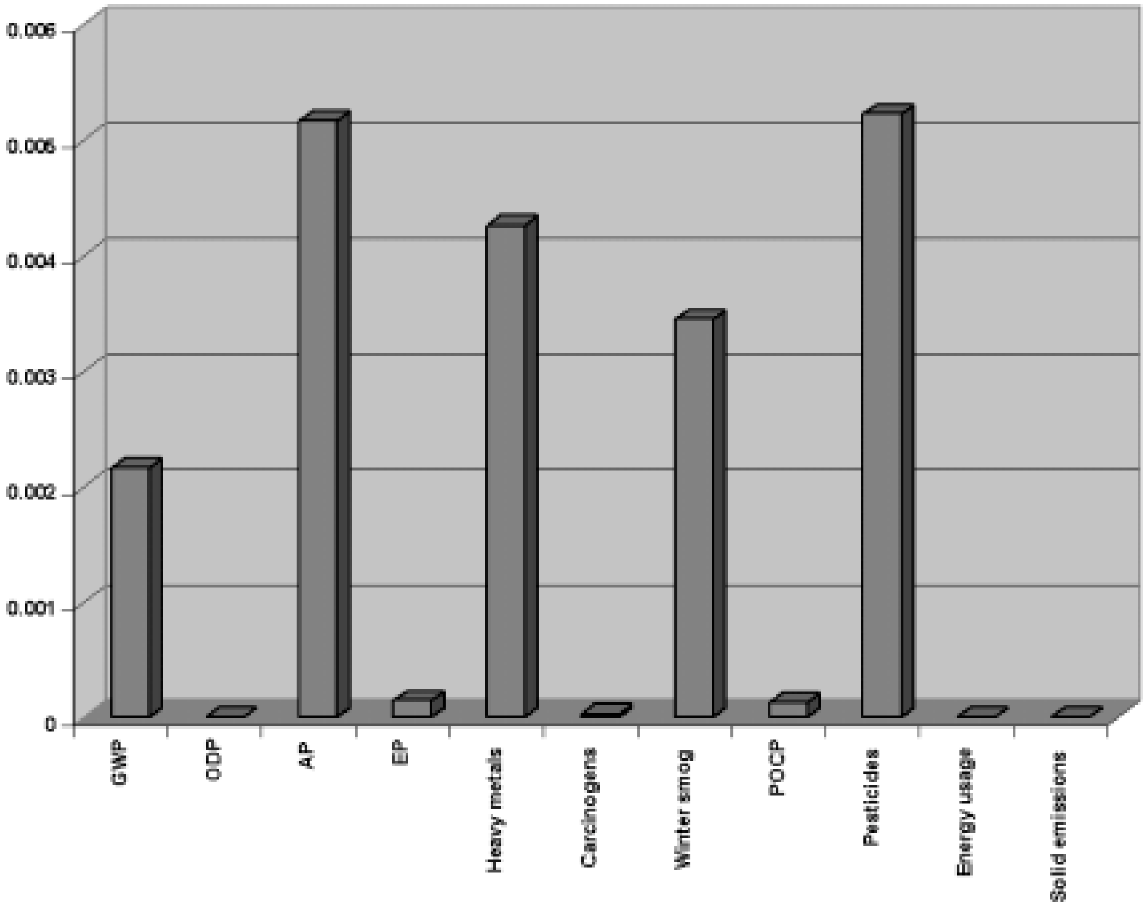

Figure 3.12: Weighting results of the Eco-indicator 95 procedure

3.4.4 Eco-indicator 99 procedure results

The Eco-indicator 99 methodology is a damage-oriented procedure, i.e. the effects of inventory data on human health, ecosystem quality and resources are considered, rather than the causes of the effects as with the first three procedures (see Section 2.5 of Chapter 2). The classified categories are subsequently different in some cases. The wool inventory does not have an influence on the radiation category (Figure 3.13). Other than wool farming (land use) and wool dyeing (ecotoxicity), all the categories are primarily influenced by steam, electricity and transport (with associated fuel production) unit processes.

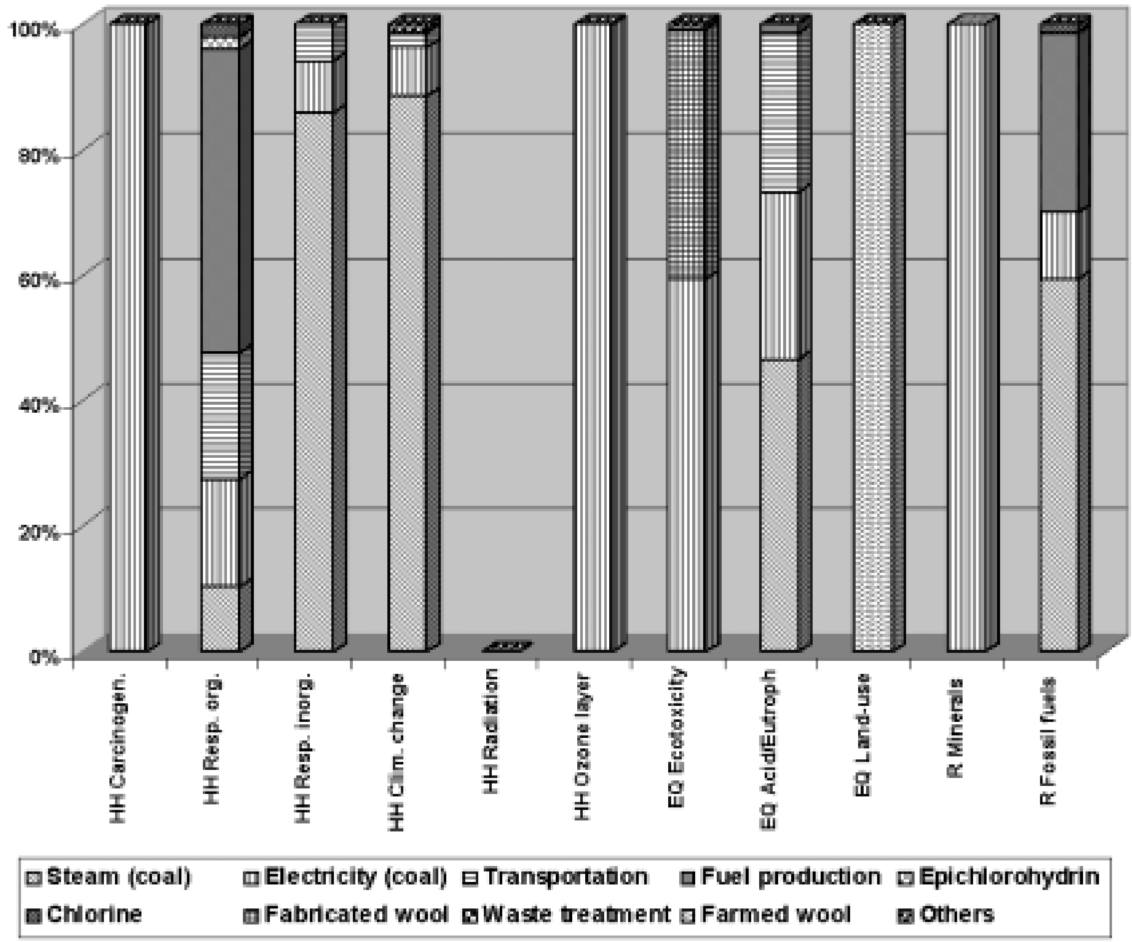

Figure 3.13: Characterisation results of the Eco-indicator 99 procedure

As with the Eco-indicator 95 methodology, Eco-indicator 99 uses Western Europe data during the normalisation step. However, the normalisation takes the damages caused by the background data into account as per the defined categories. As with the CML procedure's normalisation step, Eco-indicator 99 shows that land-use outweighs the other categories in so far as the other categories can be considered negligible (Figure 3.14).

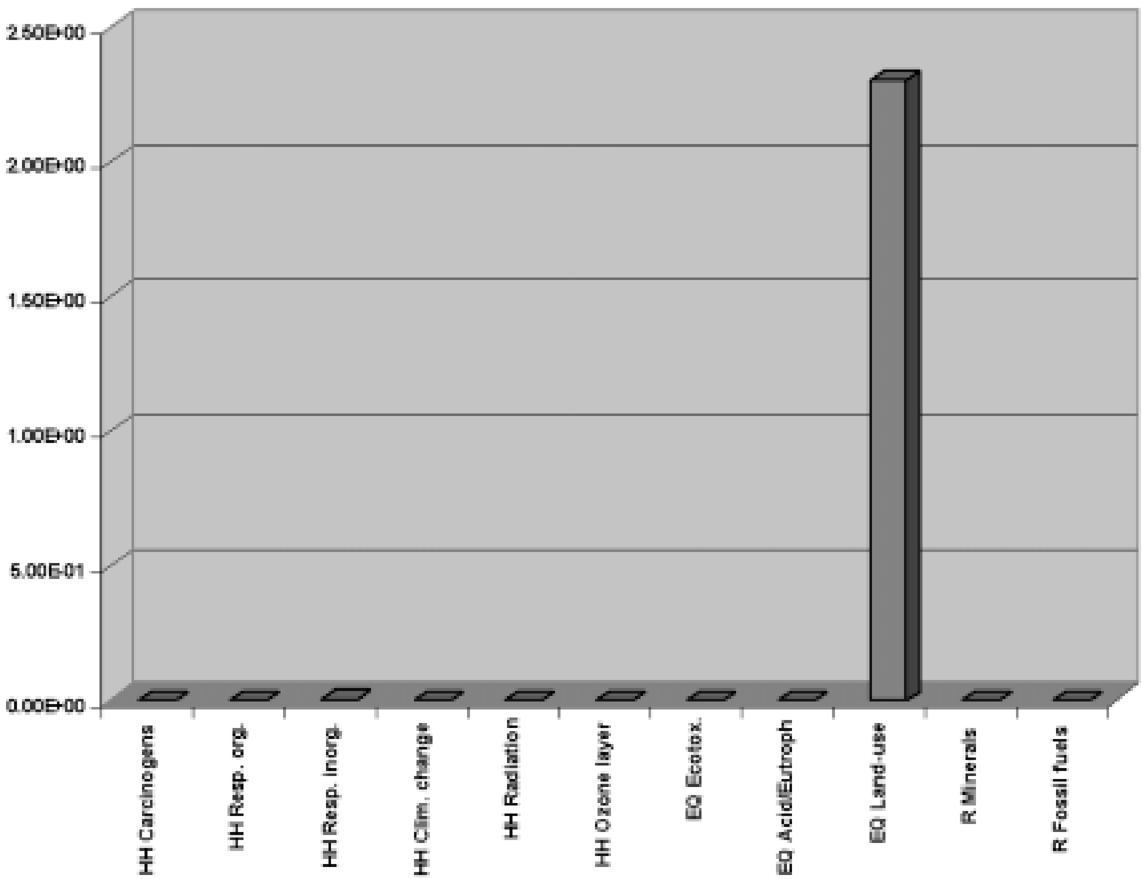

Figure 3.14: Normalisation results of the Eco-indicator 99 procedure

As discussed in Chapter 2, Eco-indicator 99 uses a panel mechanism to place subjective weights on the three end-point damages of human health, ecosystem quality and resource depletion. The panel consists of three cultural perspectives, i.e. egalitarian, individualist and hierarchist. For this case study an average of the three perspectives was taken, as is also recommended by Eco-indicator 99 [91]. Due to the normalisation step that places a strong emphasis on land-use for this study, the weighting does not influence the overall results (Figure 3.15). However, the numerical weighting values of the three end-points must be noted for purposes of further analyses, i.e. a ratio of 400:400:200 for human health, ecosystem quality and resource depletion respectively.

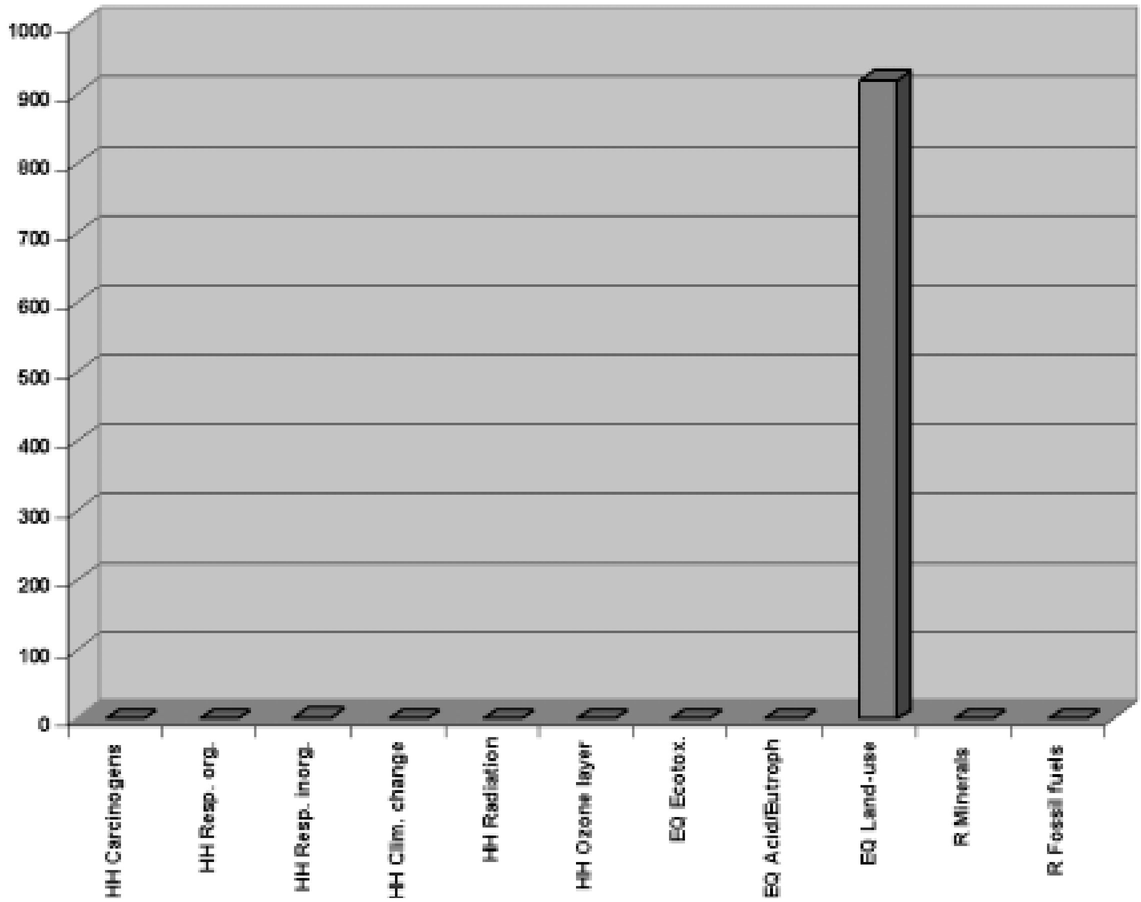

Figure 3.15: Weighting results of the Eco-indicator 99 procedure

3.4.5 EPS procedure results

The EPS methodology is also a damage-oriented model. EPS distinguishes between water used for irrigation, which is not applicable for this case study, and water used of drinking quality. In terms of the latter, wool farming and production are the most important stages in the wool life cycle, as is farming in the biodiversity category because of land-use. The difference of the EPS procedure lies in the wood and fish/meat categories. Here the net positive influence on the production rate is taken into account, e.g. carbon dioxide and nitrogen oxides result in net wood growth and meat production, while particulates, etc. would reduce meat production. In these cases short term sinks for certain emissions are considered in the modelling.

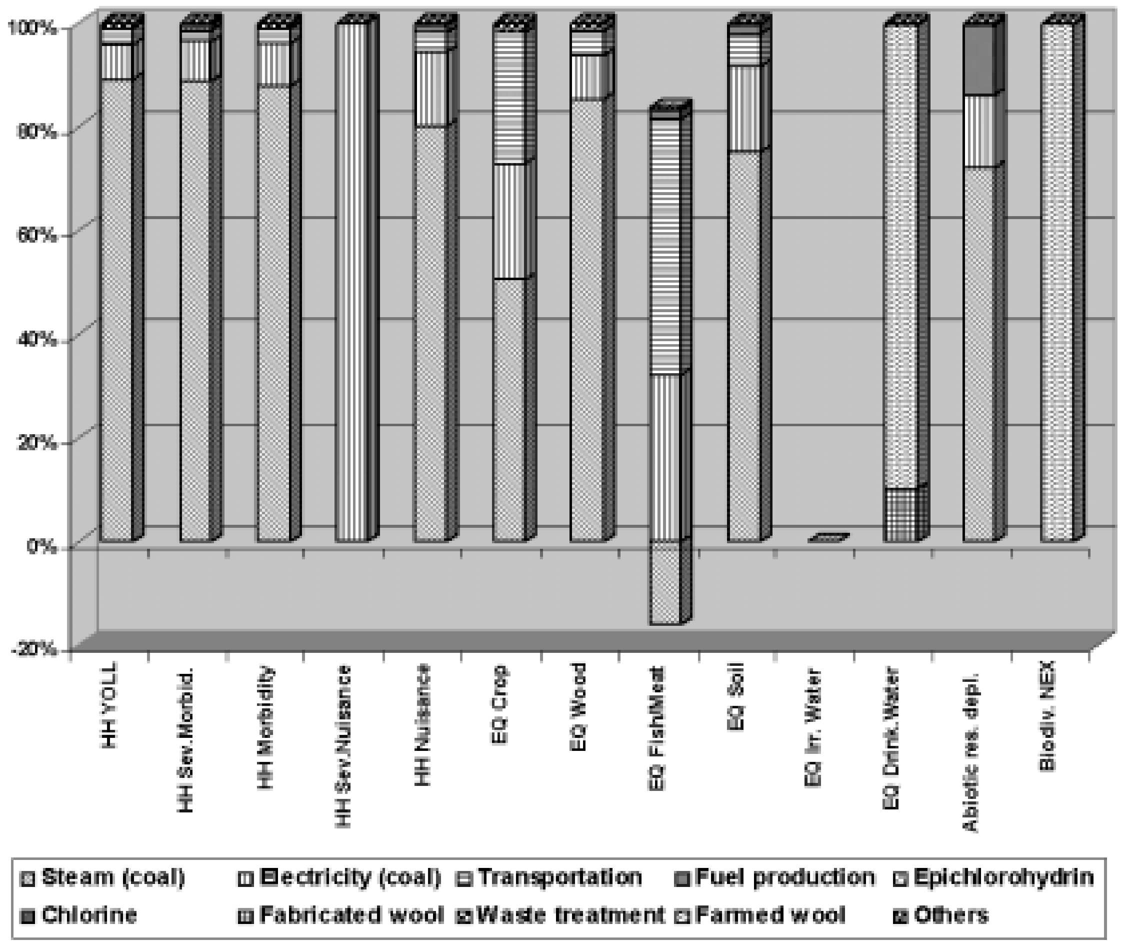

Figure 3.16: Characterisation results of the EPS procedure

As per the evaluation of Chapter 2, the EPS methodology does not include a formal normalisation step but directly calculates valuation or weighting factors for the categories based on the willingness-to-pay principle and expressed in terms of Environmental Load Units (ELUs). The results of Figure 3.17 are therefore not truly dimensionless as with the other LCIA procedures. The weighting step indicates water and land usage to be the most import contributors to the overall impacts of the wool life cycle system, with emissions impacting on human health and coal usage of secondary importance.

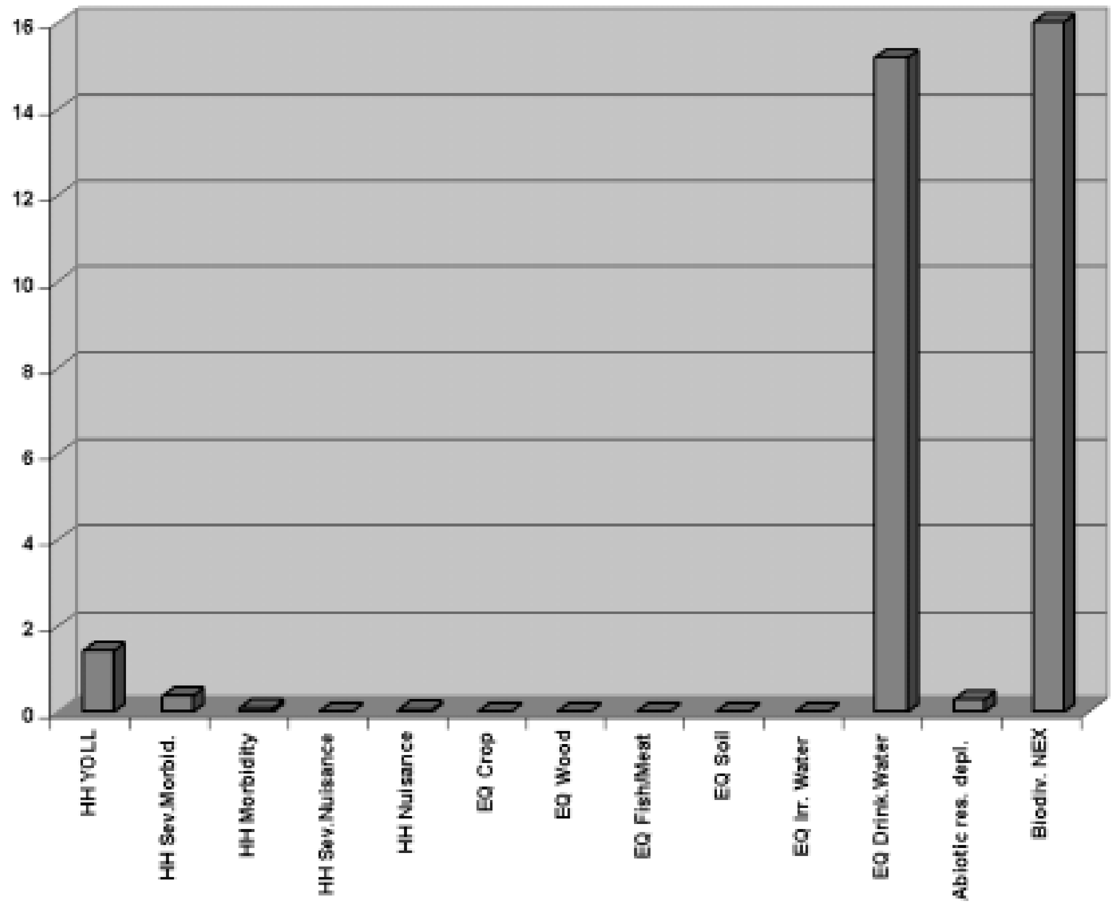

Figure 3.17: Weighting results of the EPS procedure

3.4.6 Interpretation of the results and comparison of LCIA procedures

Table 3.7 shows the most important constituents of the wool life cycle inventory (LCI) from the perspective of the LCIA elements of the CML, Ecopoints, Eco-indicators 95 and 99, and EPS procedures: classification, characterisation, normalisation and weighting. The table has been compiled by evaluating the relative contribution of the LCI profile to the elements of the LCIA phase. LCI constituents that contribute more than 1% to an element of the LCIA are included in the table. The table therefore provides an indication of the type of LCI constituents that are highlighted by the five LCIA procedures.

Table 3.7: Influence of the LCI data on the results of the existing LCIA procedures

Inventory constituents	CML		Ecopoints			EI 95			EI 99			EPS	
	C	N	C	N	W	C	N	W	C	N	W	C	W
Ammonia (air); Electricity	×	×	√	×	×	×	×	×	×	×	×	×	×
Carbon dioxide (air); Steam, electricity, transport/fuel	√	×	√	√	√	√	√	√	√	×	×	√	×
CFC-11 type compounds (air); Electricity	√	×	√	×	×	√	×	×	√	×	×	√	×
Coal usage; Steam, electricity, fuel	√	×	√	×	×	√	√	×	√	×	×	√	√
Chemical Oxygen Demand (COD); Electricity, fuel	√	×	√	×	×	×	×	×	√	×	×	√	×
Halogen aromatic compounds (AOX); Waste treatment, chlorine	√	×	√	×	×	×	×	×	√	×	×	√	×
Heavy metals (air); Electricity, chlorine	√	×	√	×	×	√	√	√	√	×	×	√	×
Heavy metals (water); Electricity, wool dyeing	√	×	√	×	×	√	√	√	√	×	×	×	×
Land usage; Wool farming	√	√	×	×	×	×	×	×	√	√	√	√	√
Nitrogen compounds (water); Electricity	×	×	√	×	×	×	×	×	×	×	×	×	×
Nitrogen oxide compounds (air); Steam, electricity, transport	√	×	√	×	√	√	√	√	√	×	×	√	×
Organics, i.e. NMVOC (air); Steam, electricity, transport, chlorine	√	×	√	×	×	√	√	√	√	×	×	√	×
Particulates/dust (air); Steam, electricity, transport	√	×	√	√	√	√	√	√	√	×	×	√	√
Pesticides (soil); Wool farming	×	×	√	√	√	×	×	×	×	×	×	×	×
Pesticides (water); Wool farming, waste treatment	√	×	×	×	×	√	√	√	×	×	×	×	×
Phosphate compounds (water); Electricity	×	×	√	×	×	×	×	×	×	×	×	×	×
Solid waste; Steam, electricity, chlorine	√	×	√	√	√	√	×	×	×	×	×	√	×
Sulphur dioxide (air); Steam, electricity, transport/fuel	√	×	√	√	√	√	√	√	√	×	×	√	√
Water usage; Wool farming, wool production	×	×	×	×	×	×	×	×	×	×	×	√	√

C, N, W Elements of the LCIA procedures, i.e. characterisation, normalisation and weighting

√ Inventory constituent is significant to the element of the LCIA procedure

In terms of classification and characterisation, the representation of inventory data differs between the five LCIA procedures: CML, Ecopoints, Eco-indicators 95 and 99, and EPS. The comprehensiveness of the inventory of a unit process determines the inclusion of inventory constituents in the classification and characterisation phases of an LCIA procedure. For example, the large number of inventory entries for electricity generation (based on a European database) results means that it is represented in most impact categories of the procedures. Due to the potential favouritism of the characterisation elements of LCIA procedures towards detailed inventory data, it is important to analyse the non-compulsory elements, i.e. normalisation and weighting, to identify the categories where a life cycle system has truly significant impacts.

The inventory constituents that are identified as having a meaningful contribution to the overall impact of the wool life cycle system after normalisation and weighting are shown in Table 3.8. A ranking value is calculated to indicate the importance that the LCIA procedures place on these inventory constituents. The ranking value is calculated from the number of LCIA procedures signifying that a constituent makes a meaningful contribution to the overall impacts and the highest priority that is placed on the constituent after normalisation or weighting:

$$R = N_P \times \frac{1}{P_P} \qquad 3.1$$

Where: R = Calculated ranking value for the inventory constituent

N_P = Highest number of LCIA procedures signifying the constituent to have a meaningful contribution

P_P = Highest priority placed on a constituent in a procedure in relation to other constituents

Table 3.8: Relative importance of LCI constituents for the LCIA procedures.

Inventory parameter	Ranking value[a]	Normalisation		Weighting	
		Number of LCIA procedures	Highest priority in procedures[b]	Number of LCIA procedures	Highest priority in procedures[c]
Carbon dioxide (air)	2	2	1	2	3
Land usage	2	2	1	2	1
Sulphur dioxide (air)	1.5	2	2	3	2
Pesticides (water)	1	1	6	1	1
Solid waste	1	1	1	1	1
Particulates/dust (air)	0.75	2	3	3	4
Heavy metals (air)	0.5	1	2	1	3
Heavy metals (water)	0.5	1	2	1	3
Water usage	0.5	0	0	1	2
Nitrogen oxide compounds (air)	0.33	1	8	2	6
Coal usage	0.25	1	4	1	5
Pesticides (soil)	0.2	1	6	1	5
Organics, i.e. NMVOC (air)	0.14	1	7	1	7

a Highest ranking value calculated between normalisation and weighting.

b Compared to other characterised and normalised inventory parameters.

c Compared to other characterised, normalised and weighted inventory parameters.

From Table 3.8, carbon dioxide, emitted by primarily steam production, and land-use, for wool farming, are the top ranked LCI constituents when considering the five LCIA procedures. However, only the Eco-indicator 95 procedure places the highest normalisation value on the carbon dioxide emissions, whilst the CML (normalisation), EPS (weighting) and Eco-indicator 99 (normalisation and weighting) procedures place the highest priority on land-use. Furthermore, the Ecopoints and Eco-indicator 95 procedures do not incorporate categories that evaluate land-use [92, 93]. This indicates the importance of the inclusion of land-use from a European perspective. However, these methods typically evaluate land-use in terms of plant species and biodiversity in European countries [94, 95, 144]. Due to variations in eco-regions [23], sheep farming in South Africa is expected to have a different effect on plant species and biodiversity [116, 117]. In terms of land use, the European-based impact assessments may therefore not apply in the South African context [145].

EPS is the only procedure that stipulates water usage as a specific environmental impact category [95]. The Environmental Load Unit (ELU) value calculated for water usage (primarily for farming) is similar to land usage and is ten times more than the third most important category, i.e. human health impacts expressed in terms of Years of Life Lost (YOLL). This indicates its potential significance as an inventory quantity. However, the calculation procedure for the ELUs, which is based on the willingness-to-pay approach, may not be appropriate for South Africa (see Section 2.7 of Chapter 2). Considering the dry region where the farming is assumed to take place, the resource usage could be an underestimate. The current approaches towards evaluating impacts due to land and water usage must be investigated further in the South African context.

Table 3.9 shows the three most important categories in the five evaluated LCIA procedures if land and water usages are excluded from the interpretation of the wool case study. The impacts are primarily associated with air emissions from steam production, electricity generation and transport requirements. The exceptions are coal (mined abiotic resource) usage, ash solid waste from steam and electricity, pesticides discharged during farming and chrome emissions from the dyeing process of the wool. The last two are only prioritised by the Eco-indicator 95 procedure. All of the LCIA procedures place a priority on the impacts of air emissions from energy supply processes. This is in contrast to the wool industry's emphasis on water quality indicators [119]. In South Africa, however, water quality indicators are more prominent in the newly introduced legislation [10] and inventory constituents that impact on these indicators will most probably receive a higher priority.

From a South African perspective (see Figure 1.16 in Chapter 1), the categories classified by these procedures are grouped into air, water, land and mined abiotic resources. Air, water and land are sub-divided still further into the characteristic human health and ecosystem quality criteria. These criteria are taken into account by these procedures either in the characterisation phase (CML, Eco-indicators 95 and

99, and EPS) or in the setting of target values for weighting purposes (Ecopoints and Eco-indicators 95). The environmental criteria considered by the five LCIA procedures are summarised in Table 3.10.

Table 3.9: Prioritised categories of the LCIA (excluding water and land)

LCIA procedure	Priority 1	Priority 2	Priority 3
CML	Abiotic depletion	Global warming potential	Acidification potential
Ecopoints	Waste (solid emissions)	Sulphur oxides emissions	Carbon dioxide emissions
EI95	Pesticide emissions	Acidification potential	Heavy metals
EI99	Respiratory inorganic emissions	Climate change	Carcinogenic emissions
EPS	Human life (fatal)	Human life (non-fatal)	Abiotic resource depletion

Table 3.10: Summary of environmental criteria considered by LCIA procedures

	CML	Ecopoints	EI 95	EI 99	EPS
Air pollution					
Human health	√	√	√	√	√
Ecosystem quality	√	√	√	√	√
Water categories					
Human health	√	√	×	√	√
Ecosystem quality	√	√	√	√	√
Land categories					
Human health	×	×	×	×	×
Ecosystem quality	√	×	×	√	√
Mined abiotic resources	√	√	×	√	√

3.5 Conclusions

In summary, the quantitative case study investigation of the commonly-used LCIA procedures in the South African manufacturing industry suggests that:

- Available LCIA procedures do not adequately incorporate the impact categories of water and land as resources. The LCIA models used in the South African manufacturing sector (typically) do not consider water as a valuable resource due the relative abundance of the resource in regions where these LCIA procedures have been developed. Also, land usage and the associated impacts on, for example, biodiversity is ill represented from a South African perspective. The consequences of economic activities in terms of the impacts (on human health and ecosystem quality) in the South African context are therefore not adequately addressed with available LCIA procedures and this can be shown with the introduction of these impact categories.

- Suitable South African water quality and land-use indicators (provided by LCIA procedures) are not region-specific to evaluate the impacts of a system on the environmental categories. Due to the diversity of the ecology in South Africa, region-specificity is an important factor that should be incorporated in a developed LCIA model for South Africa.
- Current normalisation and weighting procedures of impact categories are not consistent between published methods and are of limited use in the South African context. Normalisation and weighting values have been developed on the European continent and may not be appropriate to indicate the relative importance of the different environmental categories to the South African society.

It is therefore possible to improve on the current LCIA procedures in the South African context. An improved LCIA model could be derived with the following attributes:

- Characterisation factors are used from existing LCIA procedures that have a midpoint category approach. However, characterisation values for water and land quantity impact categories are separately determined for South Africa.
- For the classified midpoint categories, normalisation values are established that take into account the region-specific ambient states of the categories. Policies and guidelines of the South African government can be used through a modified distance-to-target normalisation approach, to group the midpoint categories into the four natural resource groups and determine the relative importance of the categories in the resource groups (see Figure 1.16 in Chapter 1).
- A panel-type method is used to determine subjective weighting values for the four natural resource groups from the perspective of the South African society.

Chapter 4: South African LCA Regions for LCIA development

This chapter introduces the region-specificity that should be considered in a South African LCIA procedure with respect to the four natural resource groups as Areas of Protection (AoP): water, land, air, and mined abiotic resources. It uses two case studies to highlight the implications of a region-specific approach:

- The manufacturing of aluminium components for assembly in automobiles.
- Leather processing for automobile components.

The case studies demonstrate that the definite impacts, and extent thereof, associated with economic activities in South Africa are dependent on where they are located.

4.1 Introduction to resource groups as Areas of Protection (AoP)

At a global level a number of environmental concerns have been highlighted [146]. Development of an LCIA methodology for South Africa must address the main environmental concerns, some of which are shown in Figure 4.1 [147].

South African activities in all manufacturing value chains, which will be evaluated with a country-specific LCIA procedure, contribute to these environmental concerns, primarily through [148]:

- Over-abstraction from surface and ground water resources.
- Salinisation of surface water due to the discharge of saline effluent from manufacturing and processing industries, irrigation of crops, the discharge of underground water pumped from mines (which also leads to acid mine drainage) and discharge of treated sewerage effluents.
- Destruction of riparian and in-stream habitat.
- Discharge of toxic substances at point and diffuse sources.
- Health and environmental impacts on groundwater resources due to diffuse pollution.
- Production of solid waste.
- Emissions of greenhouse gases and other air pollutants.

- Loss of biodiversity and valuable land, for example the degradation of wetlands in mining areas, invasion of riparian zones by invasive plants due to bad management practices, etc.
- Localised pollution through spillages and accidental leakages that may cause health problems and damage to ecosystems in the immediate vicinity.

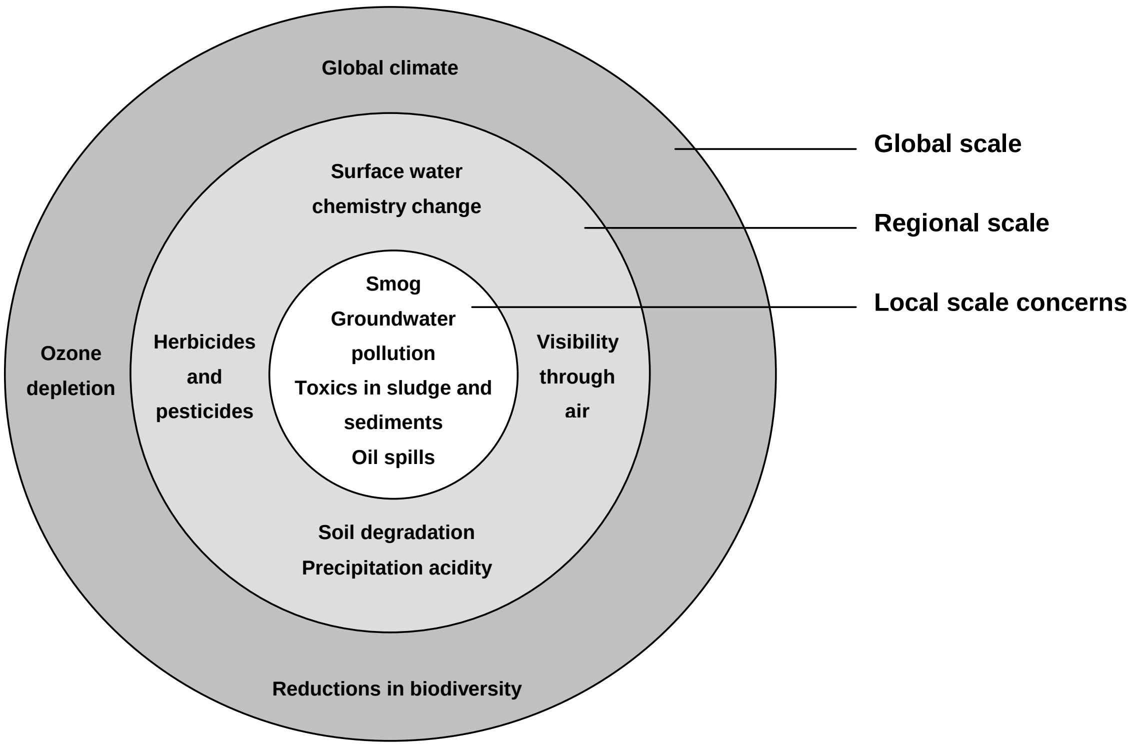

Figure 4.1: Typical environmental concerns at global, regional and local level [147]

The manufacturing sector of South Africa is further resource intensive in terms of mineral and fossil fuel usage, e.g. coal [149]. Resource depletion does not only include raw materials and energy, but also water and land [105]. However, available LCIA procedures typically deal with minerals and fossil fuel extraction only in terms of resource depletion. Land- and water use is only addressed to a certain extent in some of the methods and is therefore often not included in the analyses of systems (see Chapters 2 and 3).

Furthermore, environmental pressures associated with impacts on the air and mined abiotic resources are similar to other parts of the world (see Chapter 2). However, impacts on water and land resources differ to some extent, not only from regions external to South Africa, but also within the national borders.

4.1.1 Water resources in the South African context

Water as a resource is extensively addressed in the South African national State of the Environment report [23]. South Africa, which is a semi-arid country with an average rainfall of approximately 500 mm per year, lacks important arterial rivers or lakes. Extensive water conservation and control measures are essential as the growth in water usage threatens the available supply [150]. Ambient natural surface and ground water is recognised as a limiting factor to growth [27]. The management of these resources is therefore imperative. The main stresses include:

- Damming of all the major rivers.
- Surface and groundwater pollution from effluents.
- More than 50% conversion of wetlands in some areas, with changes in habitat affecting the biotic diversity of freshwater ecosystems.

Water resources should be subdivided into surface water and groundwater available for human use and for maintaining ecosystems. Furthermore, as a resource, water should be assessed in terms of availability and quality indicators in a LCIA procedure.

4.1.2 Land resources in the South African context

The maintenance of the biodiversity of the terrestrial resources is seen as a prerequisite for ecosystem sustainability in South Africa [23]. South Africa is ranked as the third most biologically diverse country in the world and is characterised by a wide diversity of plant and animal life, including [26]:

- over 18 000 species of vascular plants, of which over 80% occur nowhere else;
- 5.8% of the world's mammal species;
- 8% of the world's bird species;
- 4.6% of the world's reptile species;
- 16% of marine fish species;

- 5.5% of the world's recorded insect species; and
- 15% of the world's total coastal species, with approximately 12% of these occurring nowhere else.

The biodiversity is caused by a variation in climate, geology, soils and landscape forms [23] with sporadic wet and dry periods. These variations also imply fragile terrestrial systems, e.g. 91% of the country falls within "affected dry lands" as defined by the United Nations [151]. Land mismanagement due to the removal of ground cover vegetation in some of these dry lands has resulted in the dramatic increase in the loss of topsoil (35 %) [33]. The resulting fewer fertile soils is less able to support vegetation (natural or cultivated crops) in the future. Of the total surface area, 86% is classified as agricultural, although most of this is grazing land, rather than land for crop cultivation. South Africa consequently has the highest concentration of threatened natural plant groups in the world [152, 153]. South Africa currently formally conserves only 6% of the whole country and several vegetation types are under-represented, as opposed to the 10% stipulated by the United Nations Conference for Environment and Development in Rio de Janeiro in 1992 [29, 30, 31]. Furthermore, a land ownership reform process has been taking place since 1994, allowing all South Africans fair access to land and natural resources [23]. This has resulted in more than 6 million hectares of previously state-owned land now being more intensively cultivated [154]. Subsequently, the percentages of areas conserved do not indicate the intensity of land-use on those parts that are not conserved. Land-use as a resource must therefore be subdivided into the separate vegetation areas of South Africa to be conserved, as well as the required level of land-use intensity for the different vegetation areas.

4.2 Assessment of environmental impacts on specific regions

When evaluating the specific impacts associated with the product value chain of the South African manufacturing sector, special attention must therefore be given to water- and land-use and transformation. Thereby minimising the effects of loss of habitat and of prime agricultural land, as well as water, land pollution and degradation in its broadest sense. Activities in different regions along the life cycle chain of a system will have specific environmental impacts. The current LCA methodology is to compile an inventory (mass and energy balance) for the whole life cycle chain. A general LCIA procedure is thereafter conducted on the overall inventory database. In order to analyse the environmental impacts (in South Africa) accurately along the life cycle chain, an inventory should be compiled for different regions and an independent assessment undertaken for each region separately. The identified regions must be characteristic of the diversity found within the South African natural environment.

4.3 Defining regions for a South African specific LCIA methodology

The different climate, geology, soils and landscape forms are captured in eco-regions that have been defined across the globe [155]. South Africa includes 18 of these eco-regions, which are described in terms of information extracted from morphological [156] and vegetation information [31], and therefore represent the 68 vegetation types found in South Africa. The eco-regions are also generally associated with the high variability of the hydrological regime of the country, which can be seen by comparing Figures 4.2 and 4.3 [23].

The South African freshwater surface runoff has furthermore been defined in terms of 22 primary water catchments [124], which represent specific river basins, etc. (see Table 4.1). Eco-regions and vegetation types occur in multiple primary catchments. However, by grouping the primary catchments, South Africa can be subdivided into larger regions that maximise the inclusion of the eco-regions and vegetation types and thereby improve the regional-specific impacts associated with the manufacturing industry. The grouped regions, termed South African Life Cycle Assessment (SALCA) regions, whereby an improved assessment of the impacts of life cycle systems can be performed, are shown in Figure 4.4.

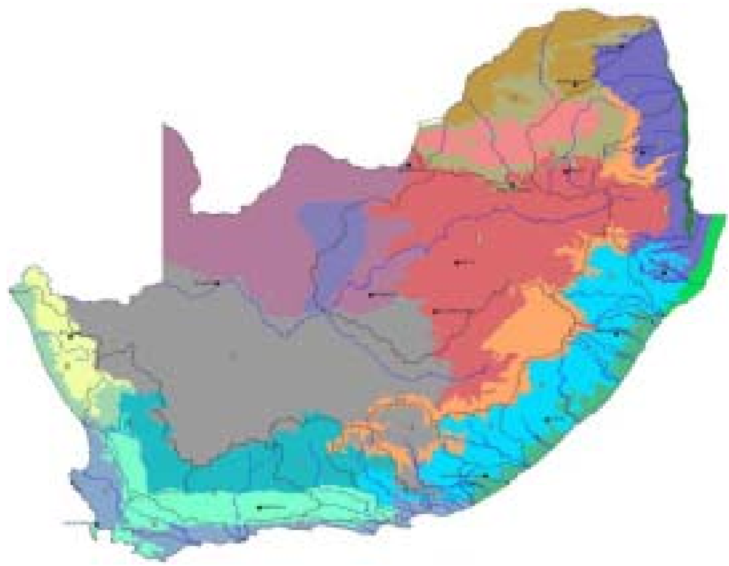

Figure 4.2: Eco-regions of South Africa [23]

A key for the figure is provided in Figure 1.4 of Chapter 1.

Figure 4.3: Surface runoff of South Africa [23]

Table 4.1: Primary water catchments represented by the SALCA regions

SALCA regions	Primary water catchments	River basins	Areas ha
SALCA Region 1	E	Olifants River (Cape) basin, Doring, Sout, Kromme, Hantams, Tanqua	4906411.07
	F	Buffels River basin, Groen, Swartlintjies	2855025.30
	G	Berg River basin, Great Berg, Breede, Salt	2529197.67
	H	Breede River basin	1552029.68
	J	Gouritz River basin, Touws, Groot, Buffels, Dwyka, Gamka, Leeuw, Olifants, Kammanassie, Traka	4513385.65
	K	Krom, Keurbooms	721587.11
	L	Gamtoos, Gouga, Groot, Kariega, Buffalo, Salt	3472988.44
	M	Swartkops River basin	262701.00
	N	Sundays River basin,Vogel, De Hoop	2122483.90
	P	Bushmans River basin	531921.06
SALCA Region 2	Q	Fish River basin, Great & Little Fish, Kat, Konap, Vlekpoort, Great Brak	3022708.20
	R	Buffalo River basin, Keiskamma,Nahoon	792959.26
	S	Kei River basin, Black Kei, White Kei, Tsomo, Little Kei	2048311.68
	T	Mzimvubu drainage basin, Bashee, Mtata, Tsitsa, Tina, Kaneka, Mzimtlana, Mtamvuma, Mzimkhulu	4663575.18
	U	Mgeni, Mvoti & Mkomazi river basins	1831056.58
	V	Tugela River basin, Mooi, Bloed, Buffalo, Sundays	2903925.83
	W	Mfolozi, Pongola, Mkuze, Usutu River basins, Mhlatuze, Black & White Mfolozi, Ngwavuma, Assegai, Mkonda, Mpuluzi, Mbuluzi, Great Usutu	5916817.55
SALCA Region 3	A	Limpopo River basin, Groot Marico, Crocodile, Matlabas, Mogol, Palala, Mogalakwena, Sand, Nzhelele, Luvuvhu	10884141.29
	B	Olifants River basin, Shingwedzi, Little and Big Letaba, Olifants, Wilge, Little Olifants, Elands, Steelpoort, Selati, Ohrigstad, Blyde	7351270.97
	X	Komati, Crocodile & Sabie River basins, Lomati, Kaap, Elands, Sand	3115333.71
SALCA Region 4	C	Vaal River basin, Wilge, Liebenbergs, Klip, Suikeboschrand, Mooi, Schoonspruit, Rhenoster, Vals, Vet, Sand, Harts, Modder, Riet	19629439.63
	D	Orange River basin, Caledon, Kraai, Senqu, Seekoei, Brak, Hartebeest, Sak, Sout	40940609.38

Figure 4.4: SALCA regions grouped from the primary water catchments

Tables 4.2 and 4.3 show the percentage of vegetation types and ecosystems included in the SALCA regions. Table 4.4 and Figures 4.5 and 4.6 indicate that more than two-thirds of the surface areas are included in the SALCA regions for approximately 90% of the South African eco-regions and vegetation types. Less than 6% of the eco-regions and vegetation types are not represented adequately, i.e. less than 60% of the respective surface areas fall within the defined SALCA regions. This amounts to one eco-region and three vegetation types, which are too widespread across the country.

Table 4.2: Hectares and percentage of vegetation types included in the regions [157]

Vegetation type	SALCA Region 1		SALCA Region 2		SALCA Region 3		SALCA Region 4	
	Ha	%	ha	%	ha	%	Ha	%
Afro Mountain Grassland	0.00	0.00	0.00	0.00	0.00	0.00	1589453.67	100.00
Afromontane Forest	254805.87	43.20	269978.56	45.77	58018.13	9.84	7022.71	1.19
Alti Mountain Grassland	0.00	0.00	308006.70	25.84	0.00	0.00	883880.35	74.16
Bushmanland	612677.83	7.36	0.00	0.00	0.00	0.00	7706738.75	92.64
Central Lower Karoo	2472719.20	100.00	0.00	0.00	0.00	0.00	0.00	0.00
Central Mountain Renosterveld	761079.75	100.00	0.00	0.00	0.00	0.00	0.00	0.00
Clay Thorn Bushveld	0.00	0.00	0.00	0.00	1630689.36	100.00	0.00	0.00
Coastal Bushveld/Grassland	0.00	0.00	1187808.94	100.00	0.00	0.00	0.00	0.00
Coastal Forest	32460.53	33.54	64329.45	66.46	0.00	0.00	0.00	0.00
Coastal Grassland	21513.14	7.52	264752.63	92.48	0.00	0.00	0.00	0.00
Coast-Hinterland Bushveld	0.00	0.00	1017943.04	100.00	0.00	0.00	0.00	0.00
Dry Clay Highveld Grassland	0.00	0.00	0.00	0.00	0.00	0.00	215669.97	100.00
Dry Sandy Highveld Grassland	0.00	0.00	0.00	0.00	0.00	0.00	5692331.46	100.00
Dune Thicket	344340.37	94.18	21274.10	5.82	0.00	0.00	0.00	0.00
Eastern Mixed Nama Karoo	737832.02	9.49	1512747.55	19.45	0.00	0.00	5528028.03	71.07
Eastern Thorn Bushveld	177384.07	18.93	759684.82	81.07	0.00	0.00	0.00	0.00
Escarpment Mount. Renosterveld	440381.89	74.64	0.00	0.00	0.00	0.00	149635.53	25.36
Grassy Fynbos	607876.72	96.12	24567.76	3.88	0.00	0.00	0.00	0.00
Great Nama Karoo	1828557.55	100.00	0.00	0.00	0.00	0.00	0.00	0.00
Kalahari Mountain Bushveld	0.00	0.00	0.00	0.00	0.00	0.00	1303974.96	100.00
Kalahari Plains Thorn Bushveld	0.00	0.00	0.00	0.00	80557.62	1.58	5012492.33	98.42
Kalahari Plateau Bushveld	0.00	0.00	0.00	0.00	0.00	0.00	2339094.42	100.00
Karroid Kalahari Bushveld	0.00	0.00	0.00	0.00	0.00	0.00	1864440.50	100.00
Kimberley Thorn Bushveld	0.00	0.00	0.00	0.00	0.00	0.00	2710260.83	100.00
Laterite Fynbos	61621.32	100.00	0.00	0.00	0.00	0.00	0.00	0.00
Lebombo Arid Mount. Bushveld	0.00	0.00	177581.69	47.64	195171.49	52.36	0.00	0.00
Limestone Fynbos	213990.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00
Little Succulent Karoo	903149.84	100.00	0.00	0.00	0.00	0.00	0.00	0.00
Lowland Succulent Karoo	2995675.02	96.64	178.67	0.01	0.00	0.00	104017.66	3.36
Mesic Succulent Thicket	194114.10	100.00	0.00	0.00	0.00	0.00	0.00	0.00
Mixed Bushveld	0.00	0.00	0.00	0.00	6239147.83	97.09	186952.58	2.91
Mixed Lowveld Bushveld	0.00	0.00	228423.49	12.98	1530720.49	87.02	0.00	0.00
Moist Clay Highveld Grassland	0.00	0.00	14161.50	1.38	113210.88	11.03	899198.69	87.59
Moist Cold Highveld Grassland	0.00	0.00	7.39	0.00	0.00	0.00	2260366.54	100.00
Moist Cool Highveld Grassland	0.00	0.00	0.00	0.00	224661.47	4.59	4671306.43	95.41
Moist Sandy Highveld Grassland	0.00	0.00	277491.54	17.85	1002574.85	64.49	274616.71	17.66
Moist Upland Grassland	0.00	0.00	4408869.81	99.99	0.00	0.00	245.76	0.01

Table 4.2 (continued)

Vegetation type	SALCA Region 1		SALCA Region 2		SALCA Region 3		SALCA Region 4	
	Ha	%	ha	%	ha	%	Ha	%
Mopane Bushveld	0.00	0.00	0.00	0.00	2096406.79	100.00	0.00	0.00
Mopane Shrubveld	0.00	0.00	0.00	0.00	261167.57	100.00	0.00	0.00
Mountain Fynbos	2746154.35	100.00	0.00	0.00	0.00	0.00	0.00	0.00
Natal Central Bushveld	0.00	0.00	1713695.87	100.00	0.00	0.00	0.00	0.00
Natal Lowveld Bushveld	0.00	0.00	1014972.03	100.00	0.00	0.00	0.00	0.00
North-eastern Mount. Grassland	0.00	0.00	2655970.24	63.38	1531534.28	36.55	2930.40	0.07
North-western Mount. Renosterveld	164083.35	100.00	0.00	0.00	0.00	0.00	0.00	0.00
Orange River Nama Karoo	0.00	0.00	0.00	0.00	0.00	0.00	5382642.60	100.00
Rocky Highveld Grassland	0.00	0.00	0.00	0.00	828126.38	34.41	1578203.89	65.59
Sand Forest	0.00	0.00	35326.87	100.00	0.00	0.00	0.00	0.00
Sand Plain Fynbos	521326.54	100.00	0.00	0.00	0.00	0.00	0.00	0.00
Short Mistbelt Grassland	0.00	0.00	481456.95	100.00	0.00	0.00	0.00	0.00
Shrubby Kalahari Dune Bushveld	0.00	0.00	0.00	0.00	0.00	0.00	3743709.95	100.00
Sour Lowveld Bushveld	0.00	0.00	188066.38	9.57	1778002.94	90.43	0.00	0.00
South and South-west Coast Renosterveld	1408370.02	100.00	0.00	0.00	0.00	0.00	0.00	0.00
South-eastern Mount. Grassland	308537.87	13.61	1051418.87	46.36	0.00	0.00	907811.75	40.03
Soutpansberg Arid Mount. Bushveld	0.00	0.00	0.00	0.00	478811.09	100.00	0.00	0.00
Spekboom Succulent Thicket	501168.29	100.00	0.00	0.00	0.00	0.00	0.00	0.00
Strandveld Succulent Karoo	379224.72	98.63	0.00	0.00	0.00	0.00	5261.02	1.37
Subarid Thorn Bushveld	3060.13	0.40	767700.00	99.60	0.00	0.00	0.00	0.00
Subhumid Lowveld Bushveld	0.00	0.00	135953.40	100.00	0.00	0.00	0.00	0.00
Sweet Bushveld	0.00	0.00	0.00	0.00	1651451.83	100.00	0.00	0.00
Sweet Lowveld Bushveld	0.00	0.00	162769.14	28.15	415349.31	71.85	0.00	0.00
Thorny Kalahari Dune Bushveld	0.00	0.00	0.00	0.00	0.00	0.00	228098.32	100.00
Upland Succulent Karoo	2792119.19	72.12	0.00	0.00	0.00	0.00	1079399.87	27.88
Upper Nama Karoo	415443.58	10.39	0.00	0.00	0.00	0.00	3584506.95	89.61
Valley Thicket	332137.74	14.73	1922826.54	85.27	0.00	0.00	0.00	0.00
Waterberg Moist Mount. Bushveld	0.00	0.00	0.00	0.00	1235143.66	100.00	0.00	0.00
West Coast Renosterveld	614070.96	100.00	0.00	0.00	0.00	0.00	0.00	0.00
Wet Cold Highveld Grassland	0.00	0.00	292401.40	30.77	0.00	0.00	657756.38	69.23
Xeric Succulent Thicket	621854.92	73.96	218988.95	26.04	0.00	0.00	0.00	0.00

Table 4.3: Hectares and percentage of eco-regions included in the regions [157]

Eco-region	SALCA Region 1		SALCA Region 2		SALCA Region 3		SALCA Region 4	
	ha	%	ha	%	ha	%	Ha	%
Bushveld Basin	0.00	0.00	0.00	0.00	3509337.69	100.00	0.00	0.00
Cape Folded Mountains	6197789.09	100.00	0.00	0.00	0.00	0.00	0.00	0.00
Central Highlands	0.00	0.00	0.00	0.00	5124708.73	98.05	101742.33	1.95
Eastern Coastal Belt	0.00	0.00	2258303.11	100.00	0.00	0.00	0.00	0.00
Eastern Uplands	729053.42	6.57	10372673.34	93.43	0.00	0.00	30.68	0.00
Ghaap Plateau	0.00	0.00	0.00	0.00	0.00	0.00	2823553.92	100.00
Great Escarpment Mount.	426039.15	5.28	2447864.45	30.32	1248120.00	15.46	3951208.82	48.94
Great Karoo	6737966.00	97.05	1367.01	0.02	0.00	0.00	203610.50	2.93
Highveld	0.00	0.00	1636960.47	8.53	1779094.43	9.27	15771745.89	82.20
Lebombo Uplands	0.00	0.00	172353.95	39.44	264696.78	60.56	0.00	0.00
Limpopo Plain	0.00	0.00	0.00	0.00	4838043.66	100.00	0.00	0.00
Lowveld	0.00	0.00	1949422.20	29.83	4586744.68	70.17	0.00	0.00
Nama Karoo	1626250.88	6.25	1536500.83	5.91	0.00	0.00	22846236.58	87.84
Namaqua Highlands	2030472.25	79.79	0.00	0.00	0.00	0.00	514356.11	20.21
Natal Coastal Plain	0.00	0.00	792531.66	100.00	0.00	0.00	0.00	0.00
Southern Coastal Belt	3984574.57	99.72	11377.26	0.28	0.00	0.00	0.00	0.00
Southern Kalahari	0.00	0.00	0.00	0.00	0.00	0.00	14275845.51	100.00
Western Coastal Belt	1735585.52	95.50	0.00	0.00	0.00	0.00	81718.67	4.50

Table 4.4: Representation of the eco-regions and vegetation types

South African eco-regions (total of 18)			South African vegetation types (total of 68)		
Percentage inclusion of an eco-region in a SALCA Region	Number of eco-regions represented	Cumulative percentage of total eco-regions	Percentage inclusion of a vegetation type in a SALCA Region	Number of vegetation types represented	Cumulative percentage of total vegetation types
100 %	7	39	100 %	37	54
> 90 %	12	67	> 90 %	49	72
> 80 %	14	78	> 80 %	54	79
> 70 %	16	89	> 70 %	60	88

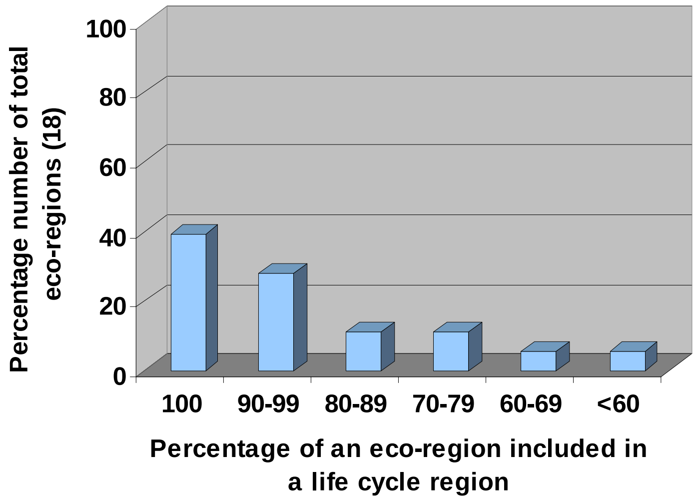

Figure 4.5: Representation of the eco-regions in the SALCA regions

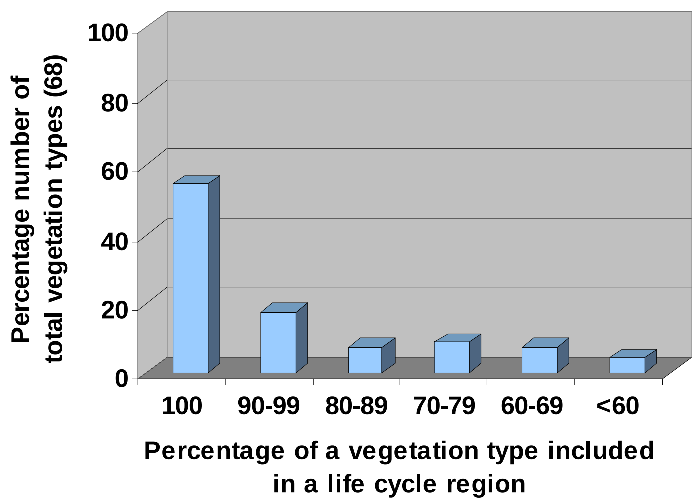

Figure 4.6: Representation of the vegetation types in the SALCA regions

The SALCA regions attempts to signify the region-specific water and land impacts associated with the South African manufacturing sector, without being too site-specific as is required by, for example, an Environmental Impact Assessment (EIA). Thereby, additional stresses of a product supply system (including attributable processes) are determined on current water, air and land resource qualities for four South African Life Cycle Assessment (SALCA) regions.

4.4 Implications of the SALCA region approach

In order to demonstrate the implications of a region-specific approach, two case studies in the South African automotive supply chain are used as illustrative examples.

The first case study evaluates the typical life cycle of lightweight (aluminium) brake callipers, manufactured and assembled in South Africa for export purposes to Europe [158]. The second case study focuses on the life cycle of a passenger vehicle's leather seat manufactured in South Africa, also for export purposes. The leather sector, and especially the supply to the Original Equipment Manufacturers (OEMs) such as BMW, Toyota, Volkswagen, etc., comprises a substantial part of the South African textiles industry [159].

4.4.1 Applying the SALCA regions to the South African metals industry

The stages in the life cycle of a South African aluminium brake calliper and the associated SALCA regions are shown in Figure 4.7. Transport processes are not included in the figure as these could be region-specific or cross-regional, e.g. bauxite is transported by sea from Australia, etc. to the east coast of South Africa, while road transportation is used for long distance haulage of materials and components within the borders of South Africa. Table 4.5 indicates the primary environmental concerns at each of the South African life cycle stages. With reference to Figure 4.7, the brake calliper system has impacts associated with the South African water, air, land and mined resources.

4.4.1.1 Water resources impact

Water usage, i.e. quantity, and water quality impacts are mainly attributable to the aluminium ingot production, primarily aqueous fluorides [160], and the generation of electricity. In terms of the latter, the majority (13.8 MWh/tonne) is used during the manufacturing of the aluminium alloy (including ingots) from bauxite and other minerals [158]. Coal-fired electricity, in turn, is primarily generated in SALCA Region 3 [136] in areas where water resources are already under stress [27] and effluents and water usage are highly regulated. Primary aluminium alloy is produced in SALCA

Region 2 with a rainfall of twice the average South African rainfall [161]. Water quantities for industrial usage are therefore readily available.

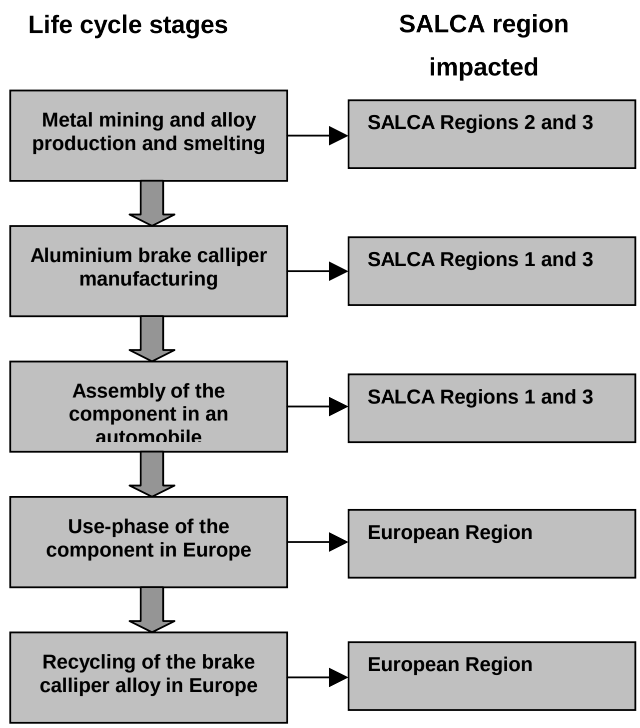

Figure 4.7: Life cycle system of an automotive lightweight brake calliper

Table 4.5: South African impacts of the brake calliper system

<table>
<tr><th>Life cycle stage</th><th>Environmental impact</th></tr>
<tr><td>Metal mining and alloy production and smelting</td><td rowspan="3">Water resource impacts due to mineral processing activities (SALCA Region 2) and energy (electricity) requirements (SALCA Region 3).

Regional and global air resource impacts due to mineral processing activities and energy requirements.

Waste disposal to land due to mineral processing activities and electricity generation.

Fossil fuel requirements for energy (SALCA Region 3).
Processing of other required minerals in the component, e.g. steel springs, have environmental impacts to a smaller degree in SALCA Regions 3 and 4.</td></tr>
<tr><td>Aluminium brake calliper component manufacturing</td></tr>
<tr><td>Assembly of the component in an automobile</td></tr>
</table>

Although European Life Cycle Impact Analysis (LCIA) methods do not consider these impacts to be as important (after normalisation), compared to the impacts on air and mined resources [158], a South African region-specific evaluation may indicate these stresses on the available natural water resources to be of significance.

4.4.1.2 Air resources impact

The South African impacts on air resources through the life cycle of an aluminium brake calliper can be allocated to the production of ingots and the alloy, the casting and assembly of the components to a minor degree, and the electricity requirements for material production, and component manufacturing to a lesser extent. The main pollutants of concern are [158]:

- Global warming gases, especially CO_2 from electricity generation and perfluorocarbons from the ingot production.
- Metals and particulate emissions from materials production and electricity generation.
- SO_2 releases from the primary ingot production and electricity generation.
- NO_x and organics emissions from electricity.

Although these pollutants are of concern and constantly monitored in terms of ambient air quality [136, 162], the regional focuses are more directed towards water and land quality issues [23, 162]. Again, this is contradictory to what a typical available LCIA methodology would indicate [158]. Also, from a life cycle perspective, the main impact on air resources associated with the brake calliper can be found in its use-phase, which is either in a region external to South Africa (as with this case study), or in multiple regions of South Africa.

4.4.1.3 Land resources impact

The principal unit processes of the aluminium brake calliper product's life cycle do not have a major impact on land resources. The raw materials for the production of the alloy, i.e. bauxite and magnesium typically produced from dolomite, are imported. In comparison to the weight of the required aluminium alloy, other materials are of relative unimportance. However, the extraction of coal, often from open pit mining, for electricity generation is often omitted. Although SALCA Region 3 is characterised by large coal reserves, the scarring of surface lands due to the extraction will require long-term rehabilitation, which must be incorporated into the evaluation of a supply chain system. Furthermore, the electricity generation in South Africa results in the disposal of large quantities of ash, although these heaps are reasonably inert [136]. Ash heaps consequently represent a land use problem in SALCA Region 3, e.g. the conversion of near-natural or agricultural land for industrial usage.

4.4.1.4 Mined resources impact

As with the land resources, the most important unit processes related to the case study's product, do not have a large impact on South African mined resources. However, using current LCIA methodologies show this category to be the most important impact [158], although the fuel required during the use-phase constitutes the main reason for the large impact (more than 90%). The only other mined resource of importance is again coal as fossil fuel for electricity generation. Liquid fuel, in the form of diesel, for transportation is also dependent on coal resources (33%) but plays a minor role. The coal usage results in the depletion of large (available) reserves in SALCA Region 3.

4.4.2 Applying the SALCA regions to the South African leather industry

The environmental impacts associated with leather manufacturing have recently been highlighted in South Africa, specifically the tannery processes [163]. However, in order to define a complete environmental profile of the supply chain and identify potential problematic areas, the complete life cycle of leather in South Africa and its related region-specific impacts must be understood. The leather life cycle (Figure 4.8) has been evaluated with conventional LCIA methodologies [164]. Again, secondary unit processes, e.g. transport and energy supply, are not shown but have been included in the assessment. The key environmental concerns are indicated in Table 4.6.

The complexity in evaluating the environmental burdens of the leather life cycle lies in the multiple regions involved in supplying the necessary leather, depending on the respective season.

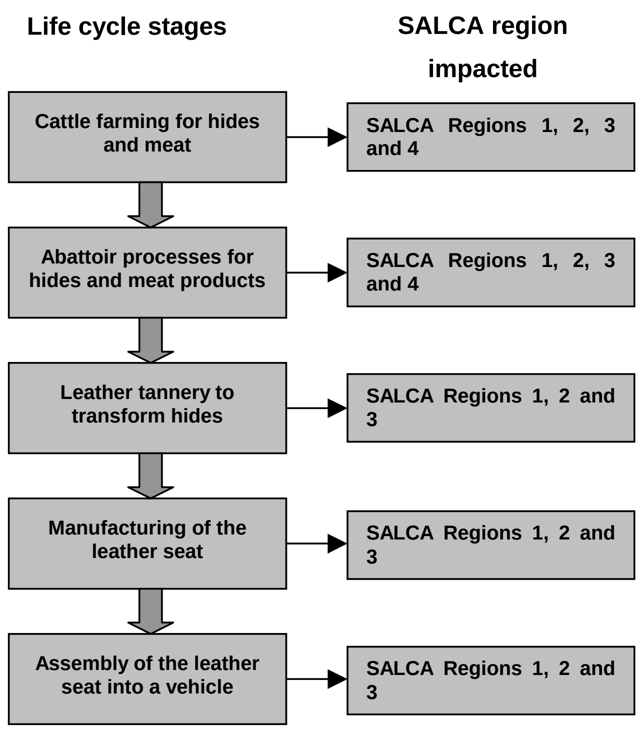

Figure 4.8: Life cycle system of an automotive leather seat

Table 4.6: South African impacts of the leather seat system

Life cycle stage	Environmental impact
Cattle farming	Water resource impacts due to farming, abattoir and tannery activities (all SALCA Regions depending on the season), as well as energy (electricity) requirements (SALCA Region 3).
Abattoir	Regional and global air resource impacts due to energy requirements (SALCA Region 3), as well as metallurgical processing for additional seat materials.
Leather tannery	Land usage for farming and waste disposal to land from the abattoirs and tanneries (all SALCA Regions), and electricity generation (SALCA Region 3).
Leather seat manufacturing	
Assembly of the seat into a passenger vehicle for export purposes	Fossil fuel requirements for energy (SALCA Region 3). Processing of other required minerals in the component, e.g. steel alloys (typically in SALCA Regions 2, 3 and 4).

4.4.2.1 Water resources impact

The impacts on water resources by the leather industry are considered significant, especially the chromium processes relating to the tanneries [119]. In addition, the farming and abattoir unit processes required in the primary life cycle should also be evaluated with reference to the SALCA Regions:

- Cattle farming occur in all regions of South Africa, but the highest intensities are in the central (SALCA Region 4), eastern (Regions 1 and 2) and northern (Region 3) provinces with a high variability in the rainfall between the affected regions. Two cattle hides are required per leather seat, amounting to water use in excess of 50 000 litres over a two-year period [164]. However, the quantity is variable and needs to be allocated between the hides and the meat, which have similar economic values. Additional impacts on ambient water qualities during farming are the result of fertilizers (KAN comprises mostly ammonium phosphates) and insecticides (acarides consists of flumethrin and piperonyl butoxide).
- The abattoir unit process requires approximately 2 000 litres of water per carcass, resulting in wastewater in excess of 1 500 litres [164]. These must again be allocated between the hides and meat products. Abattoirs are found in all areas where cattle farming occur, and the current stress on the water resources in a region must be taken into account, e.g. water supplies in the northern catchments (SALCA Region 3) have a negative balance in many cases, as do some catchments that supply the eastern areas of SALCA Regions 1 and 4, while water is in abundance in SALCA Region 2 [27]. Additional concerns are connected to the organic waste material, carcasses, and dewatered rumen, although solid wastes from the treatment of the wastewater effluent, with soaps, disinfectants, etc. are also important.
- The tanning process requires in excess of 38 000 litres of water per 140 kg grain leather [164]. A number of chemical substances, including salts, acids and chromium oxide, are used in the process with ensuing effluents (same order of magnitude as the processing water) comprising of solids, etc. with a high pH value and oxygen demand characteristics. Therefore, the wastewater effluents from tanneries contain solids with adhered organics (fats and oils), chemicals (especially nitrogen-containing compounds) and highly toxic substances. Most

important are the concentrations of chromium (III) and (VI), which are highly regulated and important toxins for aqueous ecosystems [119].

- Other impacts on South African water resources arise from the generation of electricity, primarily in SALCA Region 3, as discussed in Section 4.4.1.1.

4.4.2.2 Air resources impact

The main air pollutants are the consequence of electricity generation with attributes similar to those described in Section 4.4.1.2. Additional impacts of lesser importance include:

- Diesel combustion for farming vehicle purposes.
- Coal-fired boilers to produce steam for the abattoir and tannery processes.
- Ammonia, SO_2 and dust from the tanning process.

In general, the impacts on regional and global air resources due to the leather seat product are not considered to be of significance in South Africa [164].

4.4.2.3 Land resources impact

Impacts on land resources arise from the land surface area used during farming and the disposal of wastes, i.e. from the abattoir, tannery and electricity generation processes. In terms of the former, the different regions of South Africa have diverse grazing capacities, ranging from less than one hectare per Large Stock Unit (LSU), such as cattle, in wet regions, to 24 hectares per LSU in drier regions [117]. For areas where cattle farming are most popular, a value of 3 hectares per hide has been used or 6 hectares per manufactured leather seat [164]. It is therefore imperative that the carrying capacity of a region is taken into account in an evaluation of farming activities, which will influence the rehabilitation rate and consequent biodiversity of terrestrial ecosystems. Generated wastes throughout the life cycle also have impacts in terms of land use, i.e. land filling as a means of disposal, but the soil contamination potentials of different waste types are of increasing importance and regulated accordingly [141]. As stated in Section 4.4.1.3, the ash from electricity generation is rather inert and the quantities attributable to the leather industry quite small. The main focus, in terms of impacts on land quality, should therefore be on the abattoir and tannery processes. These impacts are similar to those on water quality (see

Section 4.4.2.1), especially chrome. Although these are typically of general concern at a national level, the background concentrations of certain substances must be regarded, e.g. ambient metal concentrations in the soils of certain regions of South Africa are above international standards due to mining and other activities [165].

4.4.2.4 Mined resources impact

The impact on South African mined resources is not extensive. Coal is utilised as fuel for boiler operations and electricity generation in the leather life cycle system [136]. The majority of collieries are found in SALCA Region 3 and the transported coal supplies therefore primarily have impacts on the reserves in this region.

4.4.3 Conclusions of the case studies

The stipulation of the regional location of economic activities in an LCA is important to determine the extent of environmental impacts, especially with regards to water, air and land resources. The capacity of the natural environment to support economic activities is dependent on the regional availability and quality of these resources. The capacity, in turn, is influenced by two factors:

- The current concentration of economic activities in a region.
- The required improvement in the natural environmental state of the regional water, air and land resources in order to ensure adequate human health and ecosystem quality.

The mined abiotic resource group is of minor importance with respect to a regional focus.

4.5 Conclusions

From a sustainable development perspective for the South African manufacturing sector, a holistic approach is required to accurately assess the environmental impacts associated with South African products and processes. Due to the diversity in the South African natural environment, evaluations should be region-specific in a South African context. Thereby, additional stresses of a product supply system (including attributable processes) is determined on current water, air, land and mined resources qualities for four South African Life Cycle Assessment (SALCA) regions.

Chapter 5: Conceptual LCIA model for South Africa

In this chapter a conceptual Life Cycle Impact Assessment (LCIA) model is developed that can be used in the South African manufacturing sector. Thereby the limitations of the existing LCIA procedures (as described in Chapters 2 and 3) are addressed. The developed LCIA model, referred to as the Resource Impact Indicator (RII) method, calculates environmental impact indicators on the four natural resource groups from a South African perspective: water, air, land, and mined abiotic resources. Through the model framework, midpoint environmental categories are grouped into the resource groups. Most of the midpoint categories have been introduced by existing LCIA methodologies, but water usage is introduced as a specific midpoint category. Also, characterisation factors for the land usage categories are proposed for South Africa.

The relative importance of the midpoint categories to a resource group is determined through the known distance-to-target normalisation and weighting method. However, the ambient environment (rather than the current background industry emissions and mined abiotic resource use data) is used to define current and target state values for the distance-to-target method for the SALCA Regions introduced in Chapter 4.

The RII method is applied to the wool case study (of Chapter 3). Thereby, the reporting of LCIA results in the South African context is shown compared to the current European-based LCIA models.

5.1 Available South African environmental data for the LCIA procedure

For the development of a South African LCIA procedure, the environmental data from a variety of sources were assessed. The process that was followed to determined which information is adequate for the LCIA procedure is illustrated in Figure 5.1. As far as possible, scientific sources were used to establish current and target values for the four main and sub-resource groups. However, in many cases only political or government sources were available. The environmental data that were used were that which were readily available in the public domain as at the beginning of 2002, although some of the sources have been renewed.

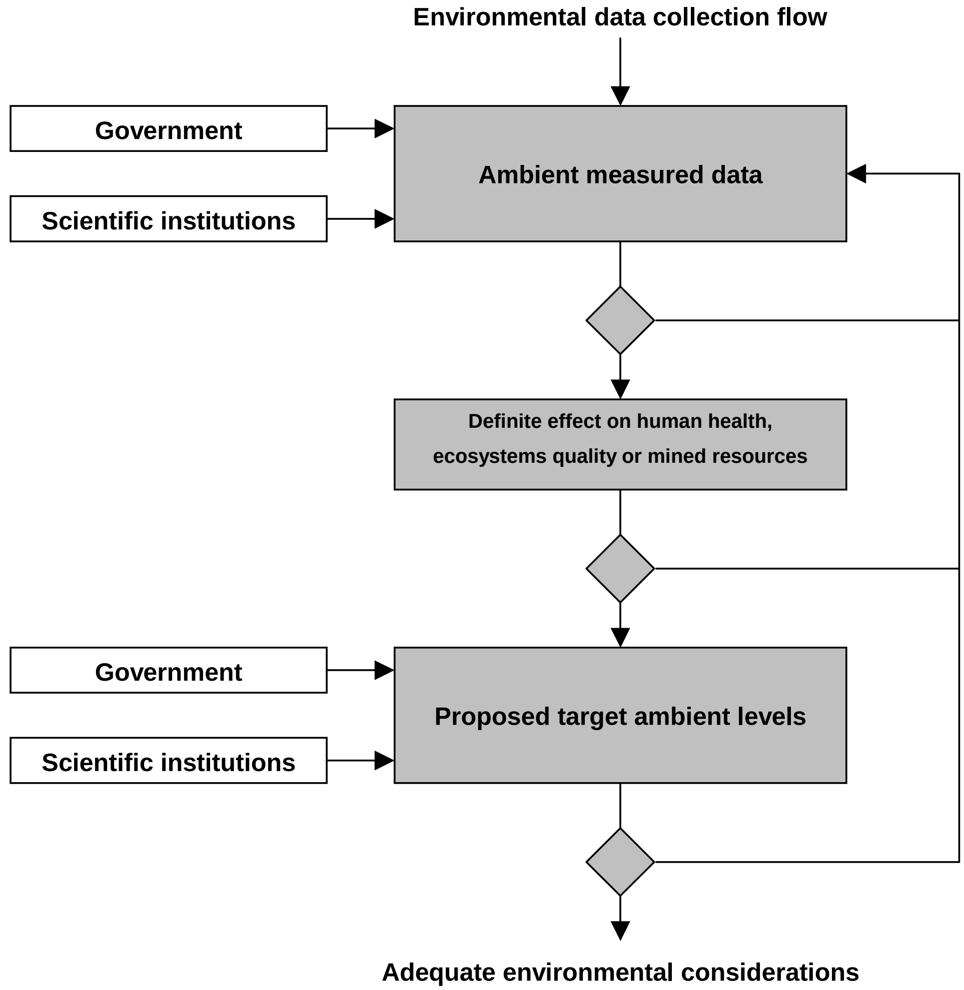

Figure 5.1: Process for South African environmental information collection

5.2 Proposed framework for a South African LCIA procedure

A modification to existing LCIA approaches is proposed, which focuses on the natural environmental resource groups (Figure 1.16 of Chapter 1) as Areas of Protection (AoP): water, air, land and mined abiotic resources. Such a modified LCIA framework for South Africa should incorporate and adhere to the requirements for a coherent set of classified environmental categories that have been proposed [166]:

- Exhaustive (completeness): all relevant criteria for the evaluation of manufacturing systems must be included. If a criterion were excluded, the framework would be redundant in theory, although an exhaustive set of criteria may not be practical.

- Cohesion: a singular criterion can determine the preference of a life cycle system or phase of a system.

ISO 14042 stipulates the identifying and classification of environmental impact categories (see Figures 2.2 and 2.3 of Chapter 2) as the mandatory phase of an LCIA [61]. The environmental midpoint categories of the CML methodology are taken with the inclusion of water use as an additional category, and with a modification to the land use characterisation mechanism. Chapter 2 shows that the CML procedure has the least limitations in the South African context, and is also the most up-to-date in the public domain (as at the end of 2002) [91].

The categories that are considered by the LCIA procedure are shown in Figure 5.2. However, the exhaustiveness of the categories should be taken into account on a case-by-case basis, i.e. the evaluation of certain systems may require the inclusion of additional environmental impact categories.

Caution must be taken where LCI constituents impact on more than one sub-resource group (see Figure 5.2), i.e. double counting [94]. Furthermore, the subsequent optional valuation steps of LCIAs should be modified to indicate the extent of impacts on the four main resource groups or AoP (also shown in Figure 5.2) from a South African perspective. These issues are addressed in the calculation procedure of Resource Impact Indicators (RIIs) for the AoP (see Section 5.3 below).

Figure 5.2 also provides examples of Life Cycle Inventory (LCI) parameters that may be included in the midpoint characterisation step of the LCIA procedure, i.e. equivalency factors. As a first approximate, the characterisation factors stipulated in the CML documentation [91] are taken for these constituents, although certain limitations can be expected in the South African context (see Chapters 2 and 3). The exceptions are the two categories of water and land use:

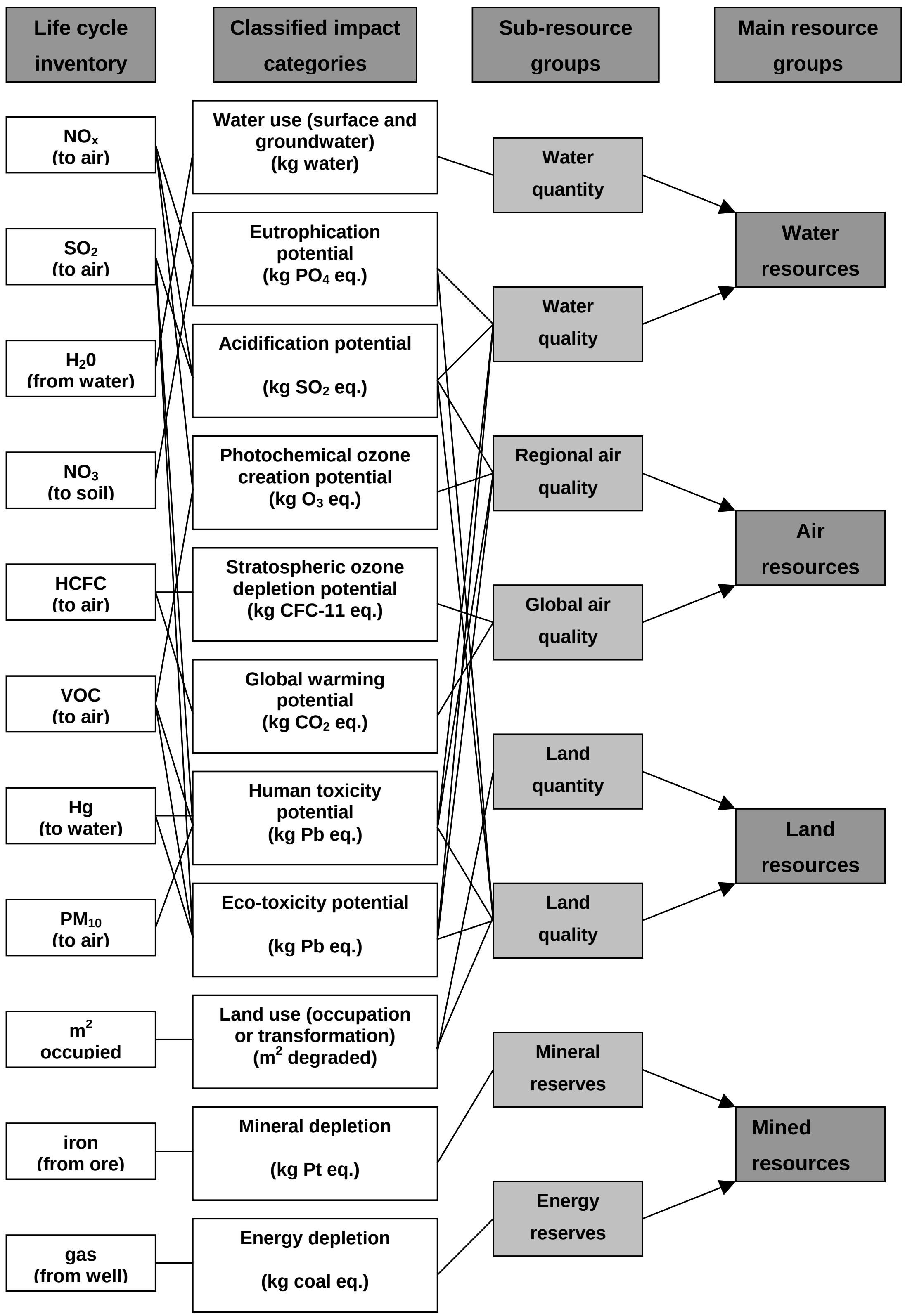

Figure 5.2: Proposed framework for a South African LCIA procedure

- No characterisation factor is introduced for the water use category, i.e. the quantity of water extracted from natural reserves (surface and groundwater) is taken as such.
- The characterisation factor (land quantity and quality impacts) for the land use category is determined from the Land Use Type (LUT) degradation severities compared to naturally reserved areas, as are shown in Table 5.1 [167]. The severity of degradation for specific LUTs is a reflection of many factors that are associated with the LUTs, e.g. water and wind erosion, salinisation, acidification and other types of soil pollution [167, 168]. LUTs have been defined, which can be utilised in the proposed LCIA procedure (see section 5.2.1. below).

The characterisation factors for the categories are provided on a website for further application purposes [169], rather than Appendices to this thesis, due to the number of LCI constituents of life cycle systems that are classified into some of the impact categories.

Table 5.1: Applied LUT degradation severities as characterisation factors [167]

Land Use Type (LUT)[a]	Land degradation severity value*	Comments
Natural	1	As a benchmark, natural rates of erosion of between 0.02 and 0.75 tonnes per hectare
Near-natural	1.75	Average taken for non-commercial (communal) croplands and veld grazing in South Africa
Intensively cultivated	1.3	Average taken for commercial croplands and veld grazing
Moderately urbanised	1.8	Average value for communal districts of South Africa
Extremely urbanised	0.9	Average value for commercial districts of South Africa
Severely /degraded	2.0	Maximum documented degradation severity for South Africa (KwaZulu-Natal province)

a The LUT specified here do not originate from the literature (see Section 5.2.1 below)

5.2.1 Defined Land Use Types (LUTs) for a South Africa LCIA procedure

A comprehensive land cover database has been compiled for South Africa [157], which defines 31 classes of land use and natural cover. Furthermore, the total areas of the South African vegetation types that are conserved in a natural pristine state have been documented [31]. The land cover classes and conservation areas are grouped into six main classes, as is shown in Table 5.2:

- Natural: near-pristine conserved areas (as a percentage of the total region area).
- Near-natural: areas that resemble the natural state, although not formally conserved.
- Intensively cultivated: areas that are used for agricultural purposes.
- Moderately urbanised: residential areas on smallholdings, typically on the outskirts of cities and in rural areas.
- Extremely urbanised: densely populated, i.e. commercial and residential use.
- Severely industrialised or degraded: areas currently used for industrial activities, or degraded due to land mismanagement practices.

Table 5.2: Grouping of the 31 land cover classes and conservation areas [157]

Main class	Sub-class	Total area (ha)	Percentage of SA
Natural	Conserved of the near-natural sub-classes	6968816.67	5.5
Near-natural	Forrest and woodland	7380729.55	5.8
	Forest	1228440.66	1.0
	Thicket and bushland	20691569.61	16.3
	Shrubland and low fynbos	42296711.32	33.4
	Herbland	224343.20	0.2
	Unimproved grassland	28335181.74	22.4
	Waterbodies	311632.25	0.2
	Wetlands	445029.25	0.4
	Barren rock	177450.49	0.1

Table 5.2 (continued)

Main class	Sub-class	Total area (ha)	Percentage of SA
Intensively cultivated	Forestry plantations	1755835.39	1.4
	Improved grassland	87203.15	0.1
	Cultivated: permanent – commercial irrigated	415776.54	0.3
	Cultivated: permanent – commercial dryland	78884.22	0.1
	Cultivated: permanent – commercial sugercane	517771.35	0.4
	Cultivated: temporary – commercial irrigated	927851.72	0.7
	Cultivated: temporary – commercial dryland	9461912.92	7.5
	Temporary – semi-commercial/subsistence dryland	3923643.72	3.1
Moderately urbanised	Urban/built-up land: smallholdings - woodland	40451.10	< 0.1
	Urban/built-up land: smallholdings – bushland	26515.80	< 0.1
	Urban/built-up land: smallholdings – shrubland	11127.10	< 0.1
	Urban/built-up land: smallholdings - grassland	138209.45	0.1
Extremely urbanised	Urban/built-up land: commercial	27997.89	< 0.1
	Urban/built-up land: residential	979751.27	0.8
Severely industrialised / degraded	Urban/built-up land: industrial/transport	54220.83	< 0.1
	Mines and quarries	27997.89	< 0.1
	Dongas and sheet erosion scars	147657.78	0.1
	Degraded: forest and woodland	1066904.75	0.8
	Degraded: thicket and bushland	2254746.14	1.8
	Degraded: unimproved grassland	2838306.33	2.2
	Degraded: shrubland and low fynbos	524269.31	0.4
	Degraded: herbland	101.95	< 0.1

5.3 South African Resource Impact Indicators based on the LCIA framework

Resource Impact Indicators (RIIs) are introduced to evaluate the impacts of LCI constituents on the four resource groups. Through the LCIA framework the calculation of these indicators is based on the LCIA phase of the ISO 14042 standard

[61]. However, environmental ambient quality or target objectives are used for the resource groups, which have been proposed as a possible alternative normalisation procedure [170], i.e. instead of actual regional industrial inventories.

The RII value that is assigned to a resource group follows the precautionary principle [163]. Thereby, the impact pathway of a LCI constituent (see Figure 5.2) that contributes to a RII value for any of the resource groups to which it contributes, is taken into account. Furthermore, the summation of the LCI contributions for a resource group is assigned as the RII for that resource group. The RII values are calculated according to the following general equation:

$$RII_G = \sum_C \sum_X Q_X \cdot C_C \cdot N_C \cdot S_C \qquad 5.1$$

Where: RII_G = Resource Impact Indicator calculated for a main resource group through the summation of all impact pathway of LCI constituents on the resource group

Q_X = Quantity of LCI constituent X released to or abstraction from a resource group

C_C = Characterisation factor for an impact category C (of constituent X) within the pathway

N_C = Normalisation factor for the impact category based on the ambient environmental quantity and quality objectives, i.e. the inverse of the target state of the impact category

and: $S_C = \frac{C_S}{T_S}$ = Significance (or relative importance) of the impact category based on the distance-to-target method, i.e. current ambient state (C_S) divided by the target ambient state (T_S)

Due to the diversity in the South African natural eco-systems, the current and target states that are required for the different environmental midpoint categories of Figure 5.2 must be defined for the specific SALCA regions (see Chapter 4). By using South African region-specific values, more accurate RIIs can be determined for the water, air, and land resource groups. The impacts on mined abiotic resources are not region-specific inside the borders of South Africa (see Section 2.7 of Chapter 2).

5.4 Research methodology to compile the ambient environmental data

The current state of the ambient environment for the four SALCA regions of Chapter 4 (in terms of the environmental resource groups of Figure 1.16 of Chapter 1), as well as the ambient environmental quality or target objectives that have been proposed as a possible alternative normalisation procedure [170], are based on the assumptions and calculations (from published data) given in Table 5.3 (as a first approximate).

Table 5.3: Approach to compile the required environmental data

Resource group	Assumptions and calculations
Water	Current and target water quantities are determined from available and projected water balances (based on maximum surface and groundwater yields, human and ecosystem consumption, and the transfer of water reserves).
	Water quality parameters are those concentrations measured at a national level in the different regions and for which minimum values are specified in terms of water quality guidelines for aquatic ecosystems availability or domestic use, i.e. for the protection of ecosystem quality and human health. For the conversion of concentration values to ambient mass levels, the available and projected water balance volumes are utilised.
Air	Regional air quality parameters are those concentrations recorded in the vicinity of industrial activities and metropolitan areas. Target values are again defined from concentration values specified for the protection of ecosystem quality and human health. Mass values are calculated from an assumed height of mixing above industrial and metropolitan areas in the Regions.
	For global air contributions, current measurements and international target concentrations are taken into account. These values are assumed equal for all the SALCA Regions.
Land	Land quantity values incorporate the current areas of all vegetation types in South Africa that are conserved in a pristine state (or a natural severity of degradation), and the international objective of 10% naturally conserved for all vegetation types.
	Land quality is already considered in the severity of degradation of land occupation or transformation. Although the severity of degradation is a reflection of many factors, additional ambient measured and target values are also introduced for metallic soil pollutants.
Mined Abiotic	Mined abiotic resource values are based on the current and projected mineral and energy reserves that are extensively documented at national level for South Africa. These values are therefore not region specific.

5.5 Water quantity state and target objectives for the SALCA regions

In each SALCA region surface and groundwater supplies must be available for agricultural, industrial and urban drinking purposes. Furthermore, the natural environment or ecosystems require a minimum amount for the continued existence of terrestrial and aqueous species.

Table 5.4: Current and projected water availability for the SALCA regions [27]

Current water availability 1996				
SALCA Region	**Assured yield[a] 10^6 m^3/annum**	**Total requirements[b] 10^6 m^3/annum**	**Total transferred[c] 10^6 m^3/annum**	**Balance available 10^6 m^3/annum**
SALCA Region 1	4625	3584	653	1694
SALCA Region 2	13462	6184	-680	6598
SALCA Region 3	7400	5693	700	2407
SALCA Region 4	7803	4584	-657	2562
TOTAL (South Africa)	**33290**	**20045**	**16**	**13261**
Projected or target water availability 2030				
SALCA Region	**Assured yield[a] 10^6 m^3/annum**	**Total requirements[b] 10^6 m^3/annum**	**Total transferred[c] 10^6 m^3/annum**	**Balance available 10^6 m^3/annum**
SALCA Region 1	4625	5427	820	18
SALCA Region 2	13462	9759	-2580	1123
SALCA Region 3	7400	8730	2514	1184
SALCA Region 4	7803	6499	-754	550
TOTAL (South Africa)	**33290**	**30415**	**0**	**2875**

a Total yield for surface and groundwater supplies.

b All usages including nature, irrigation, urban, industrial, etc.

c Transferral between national and international catchments.

The water balances that are available for the primary water catchments are therefore a function of [27]:

- the maximum or assured surface and groundwater yields, which in turn depend on the precipitation, evaporation, runoff rates, return flows, etc. of the catchments;
- the extraction of surface and groundwater reserves for human and ecosystem consumption; and
- the transfer of water reserves between primary water catchments, i.e. from a catchment with a surplus above demand to a receiving catchment with a deficit.

For the SALCA regions the current (1996) and projected (2030) water balances or quantities are shown in Table 5.4 [27]. The ambient environmental targets or objectives were assumed to equal the amount projected for the year 2030.

5.6 Water quality state and target objectives for the SALCA Regions

In addition to the physical quantities of water available in the SALCA Regions, the qualities of the respective water resources are also vital as a measure of availability for different application purposes, e.g. drinking versus industrial quality (see Figure 1.16 of Chapter 1). The South African Department of Water Affairs and Forestry (DWAF) has defined guidelines for different parameters according to the specific water usage. For the purposes of setting target environmental quality objectives, the precautionary principle was followed. Thereby, the minimum value was taken when comparing the various guidelines, and especially those for aquatic ecosystems [171] and domestic use [172] as these stipulate the most conservative target values. The water quality parameters that were considered for the purpose of the LCIA procedure, are those included in the guidelines and measured on a continuous basis by DWAF at multiple sampling points in the water catchments [124, 165]. Appendix A provides a more detailed list of measured parameters. The current state was taken as the average concentrations measured in the SALCA regions over the two years 1997 and 1998, except for toxicity constituents that are measured more infrequently. In these cases, the average value is taken for the period 1990 to 2001. The consequent current state and target objectives for the regions were multiplied with the assured yield (see Table 5.4) and are shown in Table 5.5.

Table 5.5: Measured and target water quality parameters for the regions

Inventory constituent	Target concentration	Mass load	SALCA Region 1	SALCA Region 2	SALCA Region 3	SALCA Region 4
Arsenic	10 µg/l	Current [kg]	231250	336550	510600	554013
		Target [kg]	46250	134620	74000	78030
Cadmium	0.15 µg/l	Current [kg]	18500	13462	37000	31213
		Target [kg]	694	2019	1110	1171
Calcium	16 mg/l	Current [t]	223850	265201	187220	304317
		Target [t]	74000	215392	118400	124848
Chloride	100 mg/l	Current [t]	3984438	1242543	162060	323825
		Target [t]	462500	1345000	740000	780000
Chromium	7 µg/l	Current [kg]	46250	53848	66600	93636
		Target [kg]	32375	94234	51800	54621
DOC	5 mg/l	Current [t]	94845	64537	41351	520223
		Target [t]	23125	67310	37000	39015
Fluoride	0.75 µg/l	Current [kg]	1387500	2692400	2220000	1560600
		Target [kg]	3469	10097	5550	5852
Lead	0.2 µg/l	Current [kg]	245125	242316	436600	257499
		Target [kg]	925	2692	1480	1561
Magnesium	30 mg/l	Current [t]	320050	205968.6	121360	163863
		Target [t]	138750	403860	222000	234090
Manganese	0.2 µg/l	Current [kg]	337625	646176	1013800	4346271
		Target [kg]	925	2692	1480	1561
Mercury	0.04 µg/l	Current [kg]	9250	13463	81400	54618
		Target [kg]	185	539	296	312
Nitrate	2 mg/l	Current [t]	1388	6731	6660	7023
		Target [t]	9250	26924	14800	15606

Table 5.5 (continued)

Inventory constituent	Target concentration	Mass load	SALCA Region 1	SALCA Region 2	SALCA Region 3	SALCA Region 4
H^{+} [a]	32 $\mu g/m^3$	Current [kg]	116	107	74	49
		Target [kg]	146	431	237	250
Phosphates	15 $\mu g/l$	Current [kg]	462500	1346200	740000	1560600
		Target [kg]	69375	201930	111000	117045
Sulphates	200 mg/l	Current [t]	808450	570788.8	429940	639065.7
		Target [t]	925000	2692400	1480000	1560600
TDS	450 mg/l	Current [t]	8192725	5224602	2008360	3027564
		Target [t]	2081250	6057900	3330000	3511350

a Hydrogen ion concentrations reflect the current state and target objectives with respect to pH.

5.7 Regional air quality state and target objectives for the SALCA regions

Pollutants that influence regional air quality are defined as those that are released, mixed and have environmental effects within the troposphere. Measurements of certain pollutants are performed and reported at municipal level as an annual average, as indicated in metropolitan state of the environment reports [23], and in areas with specific industrial activities [162, 173, 174]. A representative sampling spread over the SALCA Regions is therefore not available as with the water quality parameters. Values recorded in the main metropolitan and industrial areas of the SALCA regions for specific periods were consequently used to indicate the current state of the regional air quality. Where data was unavailable, measurements from municipal areas in separate regions were used. In the case of SALCA Region 4, especially, little measurement data was available. However, as the industrial activities in this region are not concentrated (except for the Vaal Triangle), the lowest concentration values of the other regions were used.

Many meteorological conditions such as inversion layers could occur and influence the atmospheric mixing height of pollutants and a mixing thickness of 2 km has consequently been proposed before [175]. However, for the conversion to mass quantities, equal mixing throughout the troposphere (approximately 10 km in thickness) in the SALCA regions was assumed over urbanised and industrial areas, i.e. the complexity of atmospheric physics (and vertical density distribution) was omitted as a first indication of the current state. For the purposes of local air quality management, the South African Department of Environmental Affairs and Tourism has set target annual concentrations for key pollutants up to the end of 2005 [176], which was used for the proposed LCIA procedure. The calculated values are shown in Table 5.6.

Table 5.6: State and targets of regional and global quality parameters

Inventory constituent[a]	Target concentration	Mass load	SALCA Region 1[b]	SALCA Region 2[c]	SALCA Region 3[d]	SALCA Region 4
Carbon dioxide	682 mg/m^3	Current [Mt]	1668.7	1505.9	1518.0	4306.5
		Target [Mt]	1600.5	1444.4	1456.1	4130.9
CFC-11 (freon)	1 µg/m^3	Current [t]	3754.8	3377.7	3405.0	9659.7
		Target [t]	2346.8	2117.9	2135.1	6057.0
Lead	0.25 µg/m^3	Current [t]	3.7	9.8	9.2	8.3
		Target [t]	2.9	6.9	8.1	6.5
Nitrogen dioxide	40 µg/m^3	Current [kg]	521.4	1190.4	1353.0	1218.1
		Target [kg]	466.9	1101.4	1292.8	1043.4
Ozone (troposphere)	100 µg/m^3	Current [kg]	466.2	1064.3	1209.7	1089.2
		Target [kg]	1167.3	2753.5	3232.1	2608.5
Particulate matter	40 mg/m^3	Current [t]	368.1	840.3	1353.0	859.9
		Target [t]	466.9	1101.4	1292.8	1043.4
Sulphur dioxide	20 µg/m^3	Current [kg]	306.7	560.2	636.7	573.2
		Target [kg]	233.5	550.7	646.4	521.7

a Mean tropospheric concentration.

b Average between Cape Town city hall and Goodwood measurements.

c Primarily the greater Durban metropolitan and Richards Bay areas.

d Primarily the Vaal Triangle, Midrand metropolitan and Mpumalanga areas.

5.8 Global air quality state and target objectives for the SALCA regions

Certain pollutants that are released into the troposphere are transferred through complex mixing processes to the upper stratosphere over time, where direct environmental effects occur on a global scale. The main concerns are global warming and stratospheric ozone depletion. In this respect ambient concentrations of carbon dioxide, methane and nitrous oxide (global warming) and freon-11 (ozone depletion) are continuously monitored at Cape Point [23].

The measurements at Cape Point are not attributable to activities in any one region, but reflect the current state on a global scale. The recorded concentrations have therefore been assumed to be similar for all four SALCA regions. In terms of target concentrations to reduce the global warming potential, the Kyoto Protocol aims for the reduction of Global Warming Potential (GWP) gases to prior 1990 levels [177]. The troposphere concentrations of ozone depleting gases are expected to level off by 2100 with the ratification of the Montreal Protocol [178]. The projected concentration was assumed as the overall target objective. The values that are used in the proposed LCIA procedure are also given in Table 5.6.

5.9 Land quantity state and target objectives for the SALCA regions

The quantity of land available for a specific economic activity is determined by the current state in a region, and the land occupation or transformation requirements of the activity.

Section 5.2.1 indicates that a comprehensive land cover database (Appendix B), together with vegetation and eco-region types, has been compiled for South Africa [30]. Using these existing Global Information System (GIS) databases, the grouped six land cover classes were mapped against the 68 vegetation types of South Africa. As 10% of all vegetation types should be conserved in pristine state as stipulated at the Earth Summit in Rio de Janeiro in 1992 [179], and assuming that the ratios of land uses in the different regions would generally stay similar, the current and target land states were determined for the four SALCA regions (see Table 5.7). Appendix C indicates the current level of vegetation conservation in South Africa.

Table 5.7: Current and target land states for the SALCA regions

Current land state (1998)						
SALCA Region	Natural (pristine) ha	Near-natural ha	Intensively cultivated ha	Moderately urbanised ha	Extremely urbanised ha	Severely degraded[a] ha
SALCA Region 1	1194574.90	18780075.60	2681013.94	12157.75	122685.38	637617.49
SALCA Region 2	1414160.01	13523549.62	3843749.97	17416.37	280091.07	2087820.96
SALCA Region 3	2960851.42	12601045.88	3722868.44	74635.50	318352.78	1773012.23
SALCA Region 4	1363059.83	49253770.84	6921246.67	112093.83	286619.93	2531838.47
TOTAL	**6932646.16**	**94158441.94**	**17168879.02**	**216303.45**	**1007749.16**	**7030289.15**
Target land state						
SALCA Region	Natural ha	Near-natural ha	Intensively cultivated ha	Moderately urbanised ha	Extremely urbanised ha	Severely degraded[a] ha
SALCA Region 1	2342812.51	17806518.35	2561409.44	11571.71	116725.92	589087.13
SALCA Region 2	2116678.80	12880124.69	3836219.83	17431.01	275348.05	2040985.63
SALCA Region 3	2145076.62	13036031.58	4119341.92	68828.03	323207.42	1758280.67
SALCA Region 4	6046862.96	45468330.25	6273244.20	101737.05	260849.67	2317605.43
TOTAL	**12651430.89**	**89191004.87**	**16790215.39**	**199567.8**	**976131.06**	**6705958.86**

a Severely degraded includes industrialised land (see section 5.2.1).

5.10 Land quality state and target objectives for the SALCA regions

The impact on land quality must also be taken into account when land is used for an economic activity. The severity of land degradation differs between human activities and has been documented for the provinces of South Africa through a workshop survey held with agricultural extension officers and resource conservation technicians, and with case studies in magisterial districts [167]. The severity of degradation for specific Land Use Types (LUT) is a reflection of many factors that are associated with the land use types, e.g. water and wind erosion, salinisation, acidification and other types of soil pollution.

The documented degradation severity values were applied to the six grouped land cover classes (see Tables 5.1 and 5.2). Similar to the land use approach proposed, whereby the development of nature is altered by human impacts [180], these severity values should be incorporated in a procedure to define the impacts associated with [181]:

- Occupation of a current land state with a similar economic activity over a period of time, i.e. as existing natural, near-natural, intensively cultivated, moderately urbanised, extremely urbanised, or severely industrialised or degraded land.
- Transformation of a current land state due to another state due to an activity, e.g. from natural to near-natural, from intensively cultivated to severely industrialised or degraded, etc.

Soil pollution, as discussed above, is taken into consideration to some extent in degradation indexes that have been calculated for the South African regions [167]. However, as the releases of certain substances to soil are typically characterised separately for human and eco-toxicity [91], current and target soil pollution levels for South Africa should be considered as well. In terms of metallic trace elements, ongoing research shows that concentrations are in general consistently spread across South Africa with reasonably high background levels associated with the local geology (except for lead) [165]. The average values for the samples and the target concentrations for South Africa are shown in Table 5.8.

Table 5.8: Measured and target soil trace elements for South Africa [165]

Inventory constituent	Average measured values[a] mg/kg	Target values mg/kg
Copper	29.4	6.6
Zinc	39.6	46.5
Nickel	39.1	50.0
Chrome (III)	80.2	80.0
Cobalt	15.7	20.0
Cadmium	0.1	2.0
Mercury	0.1	0.5
Lead	17.5	6.6

a Maximum of the NH_4EDTA and EPA 3050 extraction methods.

5.11 Mined reserves state and target objectives for the SALCA regions

The available and projected reserves of South African mined minerals and energy resources are extensively documented. For the purpose of the proposed LCIA procedure for South Africa, two of these resources are considered for the sub-groups, i.e. coal and platinum reserves.

The South African Department of Minerals and Energy calculates the annual usage and geologically and economically recoverable reserve base of coal [182]. 1997 figures indicate that 51 813 million tonnes of coal is recoverable, while 3 520 million tonnes have been extracted over a 15 year period from 1982 to 1997. If the same extraction rate is assumed, the reserve base in 2100 would be 24 171 million tonnes. The 1997 reserve value was taken as the current state of coal energy, and the 2100 value as the target state, i.e. the rate of coal mining will not increase.

Similarly, 1998 figures for platinum have been documented as 6 323 tonnes of proven and probable reserves and 29 206 tonnes of inferred reserves, i.e. a total of 35 529 tonnes that are projected to supply the market demand for approximately 186 years [183]. Again, if the annual withdrawal is assumed constant, the reserve base in 2100 would be 16 025 tonnes.

Chapters 2 and 4 indicate that the depletion of mined abiotic resources are not localised problems, but should be considered at a national level. Therefore the current state and target objectives are not defined separately for the SALCA regions. Rather, the national values are applied for the LCIA procedure irrespective of the SALCA Region where an economic activity takes place.

5.12 Current and target data used for the classified midpoint categories

The environmental dataset that is used in the RII calculations for the classified midpoint categories of Figure 5.2 is summarised in Appendix D. Where midpoint categories influence more than one resource group (see Figure 5.2), separate current and target state values have been stipulated, specifically for:

- Acidification potential: air (SO_2), water (H_2SO_4), and land (H_2SO_4).
- Human toxicity potential: air (Pb), water (Pb), and land (Pb).
- Ecotoxicity potential: aquatic toxicity potential (Pb), and terrestrial toxicity potential (Pb).
- Land use: occupation (m^2.a near-natural), and transformation (m^2 non-natural).

In terms of the latter, current and target values are therefore specified for the occupation (or coverage) of vegetation types in the SALCA Regions in pristine or near-pristine states, and the total man-made transformations of the vegetation types.

5.13 Application of the RII procedure to the wool case study

The LCI system of the wool case study (in Chapter 3) is primarily concentrated in SALCA Region 1 of South Africa. Electricity generation is the only auxiliary process that functions outside this region (SALCA Region 3). However, in order to simplify the case study, the LCI profile of Table 3.6 was applied to SALCA Region 1 solely and the RIIs calculated accordingly with Equation 5.1. The results are shown in Table 5.9.

Table 5.9: RII values calculated for the wool LCI in SALCA Region 1

Category[a]		Characterisation value	Normalisation value	Resource group	RII
WU	– kg available reserves	5.194×10^{2}	2.044×10^{1}	**Water**	2.053×10^{1}
EP	– kg PO_4^{3-} equivalence	1.048×10^{-3}	1.006×10^{-7}		
AP	– kg H_2SO_4 equivalence	9.107×10^{-2}	1.009×10^{-5}		
HTP	– kg Pb equivalence	2.457×10^{-1}	7.040×10^{-2}		
ATP	– kg Pb equivalence	3.913×10^{-2}	1.121×10^{-2}		
AP	– kg SO_2 equivalence	5.919×10^{-2}	3.330×10^{-4}	**Air**	3.370×10^{-4}
OCP	– kg O_3 equivalence	3.530×10^{-3}	1.208×10^{-6}		
ODP	– kg CFC-11 equivalence	4.272×10^{-8}	2.912×10^{-14}		
GWP	– kg CO_2 equivalence	1.134×10^{1}	7.386×10^{-12}		
HTP	– kg Pb equivalence	6.458×10^{-3}	2.841×10^{-6}		
AP	– kg H_2SO_4 equivalence	9.107×10^{-2}	1.009×10^{-5}	**Land**	4.936×10^{-1}
HTP	– kg Pb equivalence	9.183×10^{-4}	1.123×10^{-9}		
TTP	– kg Pb equivalence	3.357×10^{-4}	4.106×10^{-10}		
OLU	– m^2.a near-natural	1.333×10^{4}	4.935×10^{-1}		
TLU	– m^2 non-natural	0	0		
MD	– kg Pt equivalence	8.164×10^{-8}	4.584×10^{-8}	**Mined abiotic**	1.735×10^{-5}
ED	– kg coal equivalence	4.821	1.735×10^{-5}		

a The definitions of the abbreviations are provided in Appendix D.

If the LCI system were located in one of the other SALCA Regions, a calculated RII would reflect the actual ambient environmental state in that region. Figure 5.3 shows the relative RII values compared to the SALCA Region 1 for the wool case study LCI in the different SALCA regions and for South Africa as a whole, i.e. taking into account an overall current and target state for environmental resources. Certain LCI constituents would, however, change with respect to the specific regions, e.g. less land would be required per kilogram of wool produced in the farming stage in SALCA Region 2 compared with SALCA Region 1. This shows that not only the LCIA needs to be spatially differentiated, but the LCI as well.

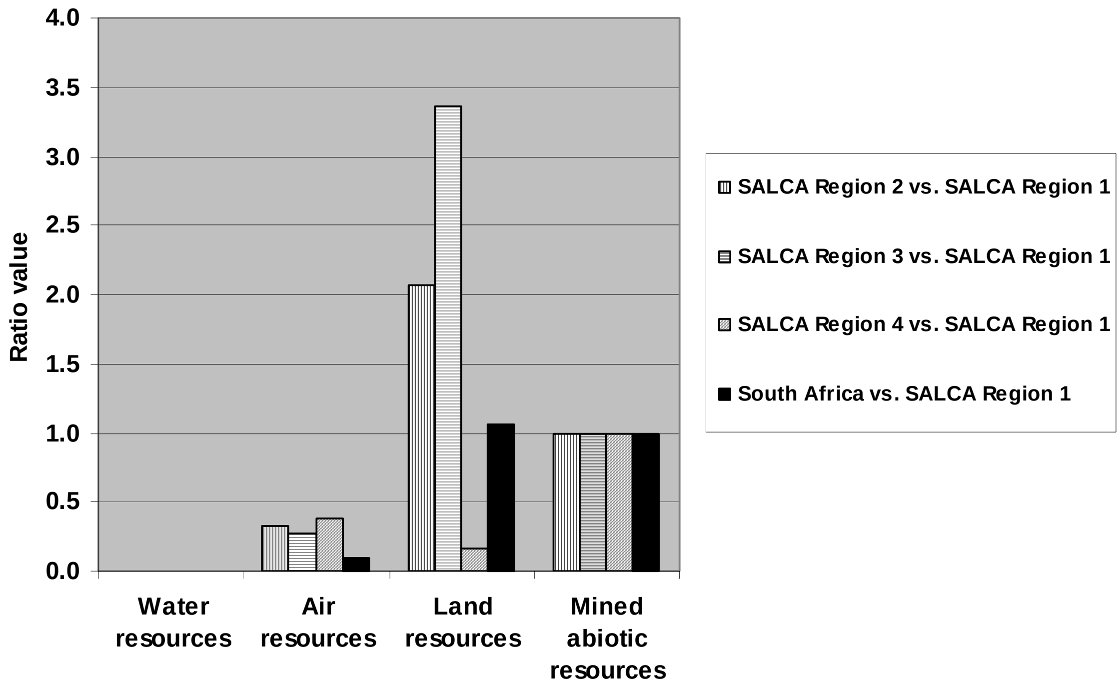

Figure 5.3: Calculated RII values for the SALCA regions and for the overall South African environment compared to the SALCA Region 1 baseline (ratio values for water resources are less than 0.005)

The RII results suggest that a wool LCI system, similar to the best practices in SALCA Region 1, placed in any other SALCA region would (overall) perform better. Only in SALCA Regions 2 and 3 would the impact on land resources be worse. The best environmental profile is calculated in SALCA Region 4, i.e. impacts on land resources are less in this region compared SALCA Region 1. This is due to the large percentage of the vegetation types that are still conserved in pristine form in this region. Also, where the ambient environmental state is considered at regional level, the environmental impact may be worse (SALCA Region 1) compared to the whole of South Africa as one region.

5.14 Conclusions

An LCIA procedure is introduced for South Africa, which includes the typical elements of the LCIA phase as stipulated by the ISO 14042 standard, i.e. classification, characterisation and normalisation. The framework of the LCIA procedure includes conventional midpoint categories, i.e. the impacts of LCI constituents are reported as equivalencies to chosen impact references. By grouping the midpoint categories the environmental impacts are assigned to four main resource groups: water, air, land and mined abiotic resources. The normalisation element applies the current ambient state and target ambient objectives in order to determine the relative importance of the midpoint categories in the respective assigned resource groups. Following the precautionary approach overall Resource Impact Indicators (RIIs) are then calculated for an evaluated life cycle system.

The RII calculation procedure simplifies the LCIA results in that the impacts of a life cycle system are only reported for the four categories: water, air, land, and mined abiotic resources. This has been demonstrated with the wool case study, which was introduced in Chapter 3. The application of the RII procedure on the wool life cycle system highlights the importance of a region-specific approach, not only for the LCIA phase, but also for the LCI phase of LCA studies.

An inadequacy of the RII procedure is to evaluate the overall environmental profile of a life cycle system, i.e. the single score approach that is often followed for internal decision-making (see section 2.1 of Chapter 2). Such a single score approach requires subjective weighting values for the resource groups. Thereby, one life cycle system can be compared to another in terms of overall environmental performances. These subjective weighting values must reflect the specific preferences of decision-makers or managers where the RII procedure is applied.

Chapter 6: Environmental Performance Resource Impact Indicators

An Environmental Performance Indicator (EPI) approach [184] is introduced in this Chapter to compare the performance of one life cycle system to another in terms of calculated RIIs. Thereby, the environmental performance of processes can be compared internally, or companies can be compared to each other, e.g. for supply chain management purposes. The Environmental Performance Resource Impact Indicator (EPRII) calculation procedure requires subjective weighting values for the natural resource groups: water, air, land and mined abiotic resources. The calculation of these weighting values is based on individual perceptions of decision-makers (or managers) that were obtained from within the (automotive value chain) manufacturing industry of South Africa, and the relative importance placed on the resource groups by the South African national government. The EPRII procedure is applied to a specific Life Cycle Management (LCM) problem in the South African manufacturing industry: the evaluation and comparison of the environmental performances of the first-tier suppliers of Original Equipment Manufacturers (OEMs).

6.1 Introduction to the Environmental Performance Indicator (EPI) approach

The EPI approach applies a simple ranking value procedure, which has been suggested for project and technology evaluation purposes [184]. The procedure assigns a qualitative impact value of 1, 0, and –1 to the resource groups, based on the RII performance of one system compared to another (termed baseline). A value of 1 therefore indicates a better environmental performance of one system compared to the baseline; -1 a worse performance; and 0 indicates no significant difference in the calculated RII values for the systems. For example, for the wool case study (of Chapter 3) the LCIs of the systems are assumed to be similar, whilst the different systems operate in specific eco-regions. The results of the RII comparisons with the wool system in SALCA Region 1 as the baseline (see Figure 5.3 of Chapter 5) are shown in Table 6.1. A –1 value is assigned where the ratio of RII values is higher than 1; and a value of 1 where the RII value for SALCA Region 1 is higher. A value of 0 depicts that there is no difference between the evaluated system and the baseline (or reference) system.

Table 6.1: Assigned ranked values for the wool systems in different regions

	Ranked value			
Resource group	**SALCA Region 2 vs. SALCA Region 1**	**SALCA Region 3 vs. SALCA Region 1**	**SALCA Region 4 vs. SALCA Region 1**	**South Africa vs. SALCA Region 1**
Water resources	1	1	1	1
Air resources	1	1	1	1
Land resources	-1	-1	1	-1
Mined abiotic resources	0	0	0	0

Subjective weighting values for the resource groups are used to calculate an overall single score or Environmental Performance Resource Impact Indicator (EPRII) for the evaluated systems (compared to the baseline system), based on the following equation:

$$EPRII_S = \sum_G EPI_G(RII) \cdot w_G \qquad 6.1$$

Where: $EPRII_S$ = The Environmental Performance Resource Impact Indicator for a system

$EPI_G(RII)$ = Environmental Performance Indicator (-1, 0, +1) for a resource group determined by comparing the Resource Impact Indicator (RII) calculated for a system for the resource group with the RII of the baseline

w_G = Subjective weighting value for each of the resource groups

A positive summed value (or EPRII) of the multiplied results would indicate that the evaluated system has a better overall environmental performance compared to the reference system.

6.2 Methodology to determine weighting values for the resource groups

Weighting factors for the natural resource groups are primarily determined through the Analytical Hierarchy Process (AHP), which is a known multi-attribute weighting method for decision support [185, 186, 187]. The AHP has been used before for the purposes of weighting criteria and indicators for sustainable development in certain industry sectors [188, 189] and for solving complex decision-making problems in various disciplines, e.g. public policy [190], strategic planning [191], viability determination [192], forecasting [193] and project management [194].

6.2.1 The AHP methodology

The AHP model is based on a pair wise weighting approach [195], whereby the resource groups are compared to each other to establish each criterion contribution (priority vector) to the objectives, i.e. to maximise the environmental performances of a life cycle system.

A pair wise comparison matrix (A) is defined, which is of the fourth order, i.e. four resource grous are compared. The pair wise comparison matrix consists of elements (aij). Each element represents the value when criterion i is compared to criterion j. A fundamental 1 to 9 point scale has been introduced for the pair wise comparisons [185]. Other proposals involve logarithms, geometric powers and negative numbers [196]. The purpose of the AHP model is to simplify complex problems and complex scales complicate the overall procedure. Furthermore, the precise format of the scale is immaterial as the comparison of the criteria is still the perception of the decision-maker. Therefore, the 1 to 9 point scale is taken as adequate for the purposes of this study.

The priority vector (ω_i, i=1,...,4) is obtained by solving the eigenvector problem [197]. As has been stated above, the priority vector is representative of the criterion contribution in the AHP model. The principal eigenvalue is denoted by the symbol λ_{max}. The following equation determines its relation to the pair wise comparison:

$$A \cdot \omega = \lambda_{max} \omega \sum_{i=1}^{4} \omega_i = 1 \quad (6.2)$$

The inconsistencies of the judgments (or pair wise comparisons) are measured by means of a Consistency Index (CI) [197]. If the reciprocal comparison matrix is consistent then λ_{max} = 4, and CI = 0. The relationship between λ_{max}, the order of the comparison matrix (4) and CI is shown in the following equation:

$$CI = \frac{\lambda_{max} - 4}{3} \tag{6.3}$$

A normalisation measure is further proposed [185], referred to as the Consistency Ratio (CR), in order to overcome the order dependency of CI. A CR of 1 indicates that the pair wise comparison matrix is totally random and thus constitutes a low precision [197]. A CR of less than 10% is generally acceptable [185]. For a comparison matrix of the fourth order a CR of 8% is more acceptable [197]. The CR is calculated by dividing the CI with the variable RI, which is the Random (Consistency) Index for *n* order matrices. RI values have been calculated and published in the original AHP methodology documentation [185].

If the CR is greater than 0.08 a decision-maker should consider the re-evaluation of the resource groups. However, the practice of adjusting the comparisons to achieve a CR of 0 is not advisable [196]. By attempting to achieve a zero CR the decision-maker is inherently biased toward one criterion in a pair wise comparison. If the comparisons are considered to be fair a CR greater than 0.08 may be accepted. A sensitivity analysis is then advisable to establish the impact of the inconsistency.

6.2.2 Advantages and disadvantages of applying the AHP methodology

From an analytical viewpoint, the AHP produces a larger spread of weights compared to other weighting methods and has some unique modelling features for hierarchy trees [198]. However, some researchers criticise the AHP methodology as lacking a firm theoretical basis, which must be noted, although its wide application is proof that AHP is a usable decision-making tool [194]. Some of the criticisms regarding the AHP are as follows:

- Decision-makers may be biased towards certain objects (or resource groups). It is therefore essential that a representative sample is used and that the results are reported as characteristic of the specific kind of decision-maker that has been chosen. Where a group of decision-makers is used the geometric mean is the representative average of the group, as the standard average does not produce the proper reciprocal [196].

- Rank reversal is a possible weakness of AHP [199, 200, 201]. Rank reversal occurs if an irrelevant alternative is added or removed from the comparisons. This contradicts the utility theory that implies that a non-optimal alternative cannot become optimal if alternatives are added or deleted. Rank reversal could also occur if an error is made in the evaluation of the pair wise comparisons [201]. In the case of this study, there is no opportunity to add new resource groups, and it is therefore only essential to perform the pair wise comparisons correctly.
- AHP was designed for a maximum of 10 objects, i.e. the RI values, etc. were only calculated for up to 10 objects in a matrix. Although some researchers have formulated methodologies for larger matrices, it becomes impractical to work with such large matrices. Furthermore, the number of comparisons increases substantially as the size of the hierarchy increases [193]. The comparisons that are needed to pollinate the hierarchy are proportionate to the matrix size (n) by (n(n-1)/2). A large number of comparisons could therefore lead to information overload and cause errors in judgements. However, in this study only four objects (or resource groups) are compared.

From Section 6.2.1, participants of a workshop or survey are requested to compare the importance of two resource groups at a time, i.e. which of the two resource groups is more important, and how much more important. The participants indicate the strength of their preferences by using integers from one to nine [185, 186] as is shown in Figure 6.1. As there are four resource groups, six comparisons are required to determine a weighting factor for each resource group through the AHP method. With other weighting methods, such as direct weighting methods, the participants compare and weight all four of the resource groups simultaneously [202]. Although more comparisons are required with the AHP, inconsistencies in the preferences of the participants can be checked [195]. Table 6.2 illustrates such a hypothetical example.

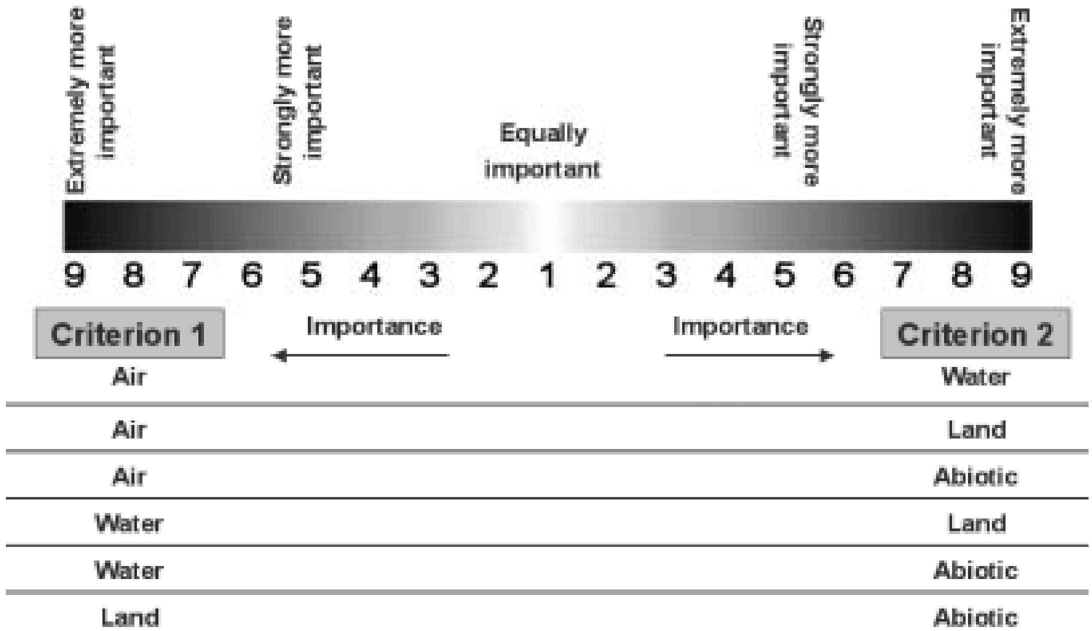

Figure 6.1: Integer values indicate the preference between two resource groups

Table 6.2: Hypothetical inconsistency from indicated preferences

Comparison	Result (importance preference)
Air resources vs. Water resources	Air resources
Air resources vs. Land resources	Land resources
Air resources vs. Mined abiotic resources	Mined abiotic resources
Water resources vs. Land resources	Water resources
Water resources vs. Mined abiotic resources	Water resources
Land resources vs. Mined abiotic resources	Land resources
Hypothetical result of importance	**Air > Water > Land > Mined abiotic > Air (inconsistency detected)**

A previous study in South Africa compared the outcome of the AHP and direct weighting approaches, where a straight interface between the researcher and the participants was possible through workshops [203]. The research showed that both weighting procedures calculated similar results. Furthermore, South African participants had less difficulty comprehending the required comparisons of the AHP method. Therefore, this methodology was chosen as the most appropriate procedure to establish the relative weighting values for the natural resource groups in the South African context.

6.2.3 Application of the AHP approach to establish weighting values from the perspectives of the South African manufacturing industry

A survey was carried out through questionnaires, which were circulated in the second half of 2002 (see Tables 6.3 and 6.4) to analyse the weighting values of the resource groups from the perspectives of two South African manufacturing industry sectors, as defined by the Standard Industry Classification [204], which form part of the South African automotive value chain. These manufacturing sectors are introducing sustainable development aspects into company decision-making processes and are thereby also considering the environmental performances of the respective product value chains [205, 206]. The weighting values should reflect the importance of the resource groups from a decision-making or management perspective where these values are applied to specific Life Cycle Management (LCM) problems. Therefore, with respect to the control of budgets that influence the environmental performances of products in the specific sectors, two types of industry participants were chosen for the survey within the manufacturing sectors:

- Managing directors of South African companies in the automotive supply chain, representing first, second and third tier suppliers [207]. Some 43 companies participated in the survey (representing approximately one-quarter of the listed automotive supply industry in South Africa), with acceptable Consistency Indexes and Ratios for all of the pair wise comparisons. This is approximately 25% of all the surveys that were circulated.
- Financial directors of organisations or companies, primarily in the process-related manufacturing industry sector of South Africa, which are listed in the company database of PricewaterhouseCoopers South Africa. Thirteen companies participated in the survey with acceptable Consistency Indexes and Ratios for all of the pair wise comparisons. This is approximately 3% of all the surveys that were circulated.

Table 6.3: AHP survey design for the determining of weighting values

How important do you think the following environmental resource groups are in relation to each other and in terms of evaluating development projects? (refer to the descriptions of the groups in Table 4.8														
Comparison number	Resource group A	Resource group B	Which group is more important? A or B		How much, do you think, is the one more important than the other? (1 = equally important, 9 = much more important)									
1	Air	Water	A	B	1	2	3	4	5	6	7	8	9
2	Air	Land	A	B	1	2	3	4	5	6	7	8	9
3	Air	Mined	A	B	1	2	3	4	5	6	7	8	9
4	Water	Land	A	B	1	2	3	4	5	6	7	8	9
5	Water	Mined	A	B	1	2	3	4	5	6	7	8	9
6	Land	Mined	A	B	1	2	3	4	5	6	7	8	9

Table 6.4: Description of the natural resource groups in the circulated survey

Resource group	Description and examples
Water	• Human health impacts, e.g. toxic metals and organics, smell, taste, etc. • Ecosystem toxicity, i.e. lethal to aquatic plants and animals • Acidification, e.g. acid rain and acid drainage • Eutrophication, e.g. nitrates and phosphates • Water availability and use • Loss of biodiversity
Air	Region effects of air pollution: • Human health impacts, e.g. toxicity, respiratory (asthma), smell, noise, etc. • Ecosystem toxicity, i.e. lethal to aquatic and terrestrial plants and animals • Acidification, e.g. acid rain Global effects of air pollution: • Global warming potential, e.g. CO_2, CH_4, etc. • Stratospheric ozone depletion potential, e.g. CFC-11, etc.
Land	• Transformation of land or land use • Loss of topsoil, i.e. erosion • Loss of terrestrial biodiversity • Human health impacts, e.g. toxic metals and organics on soil, etc. • Ecosystem toxicity, i.e. lethal to terrestrial plants and animals • Acidification, e.g. acid rain and acid drainage
Mined abiotic	• Mineral use • Non-renewable fossil fuel use

The pair wise comparisons of the AHP (ration comparisons) were translated into relative weights through the known matrix eigenvalue approach [208] described in Section 6.2.1. Web-HIPRE is a free internet interface that allows the user to process

AHP models and was used for this translation [209]. Thereby the relative weights for the resource groups were obtained for each participant in the survey. These relative weights add up to a total value of 1.

Commonly used group decision-making techniques, such as the Delphi method or nominal group technique, have been used together with the AHP to obtain consensus amongst participants [187, 188, 189]. However, there was no direct interaction with the industry participants as a group throughout the study (nominal group technique) and multiple survey interactions were not possible (Delphi method) due to the availability of the participants. These techniques were therefore not used. Nevertheless, two techniques have been documented to aggregate and group the individual judgements obtained from the AHP surveys [210]:

- Aggregation of Individual Judgements (AIJ), whereby the judgements (pair wise comparisons) are combined before translation to relative weights. Thereby, the geometric mean of the selected integers (by the participants) for each comparison is obtained before the relative weights are calculated through the formula of Section 6.2.1.
- Aggregation of Individual Priorities (AIP), whereby all individual judgments are first translated to relative weights and then combined. Thereby, relative weights are calculated for the criteria as determined by each participant through the formula of Section 6.2.1. Thereafter, the geometric mean values are calculated for the criteria from the spread of relative weights.

It has been argued that the choice of combination method depends on whether the group is assumed to act as a unit or as separate individuals [210]. Individual identities, such as the individual levels of inconsistency, are lost with the AIJ technique. Although the circulated survey represents the response from two specific industry sectors, the groups were not homogenous as they consist of individuals with respective values. The AIP technique was consequently the more appropriate combination method.

6.2.4 Evaluating government expenditure to determine weighting values

The weighting values of the natural resource groups were further evaluated with the priorities of the South African national government. In this case the expenditure trends of the national government on air, water, land and mined abiotic resources in the annual budget were considered. Table 6.5 shows the allocation routes for funding in terms of the four resource groups. Of the total annual national budget that is allocated for environmental issues, the fractions that are distributed to the four resource groups determine the relative priorities or weights of the resource groups.

In the 2002/2003 financial year 2% of the total annual budget of the national government (R287.9 billion or £19.7 billion at the end of January 2003) was allocated to environmental issues [211]. This equals a total of R 6 625 million (or approximately 1 billion US$) with the following distribution to the four environmental resource groups:

- Air resources - R 252 million (4%)
- Water resources - R 3 512 million (53%)
- Land resources - R 1 118 million (17%)
- Mined abiotic resources - R 1 743 million (26%)

These values do not include the funds that have been dispersed from the national budget to provincial and local governments, where the authorities would have individual priorities in terms of addressing provincial and local environmental issues.

Table 6.5: Government directorates and programmes allocated to environmental issues for the 2002/2003 financial year [211]

Departments		Directorates and sub-programmes	Expenditure routes and allocation[a]
National annual expenditure on environmental issues	Environmental Affairs and Tourism	**Environmental planning and coordination**	Air, water and land resources R 121 639 407.66
		Marine and coastal management	Water resources R 269 824 298.47
		Tourism	Not applicable
		Environmental quality and protection	
		• **Air quality management**	Air resources R 3 293 855.70
		• **Chemical and hazardous waste management**	Air, water and land resources R 4 751 791.83
		• **Waste management**	Air, water and land resources R 6 533 713.77
		• **Climate change and ozone layer protection**	Air resources R 4 670 795.38
		• **Environmental resource economics**	Air, water and land resources R 820 764.04
		• **Financial assistance (poverty relief projects)**	Not applicable
		• **Contribution to SA Weather Service**	Air resources R 84 590 534.26
		Biodiversity and heritage	Water and land resources R 267 294 607.07
		Auxiliary and associated services	Air, water and land resources R 24 423 230.63
	Minerals and Energy	**Promotion of mine safety and health**	Not applicable
		Mineral development	Mined abiotic resources R 97 590 790.41
		Energy management	Mined abiotic resources R 1 023 019 267.88
		Associated services	Mined abiotic resources R 622,184,492.46
	Land Affairs	**Surveys and mapping**	Land resources R 61 884 712.38
		Cadastral surveys	Not applicable
		Restitution	Not applicable
		Land reform	Not applicable
		Spatial planning and information	Land resources R 15 204 130.60
		Auxiliary and associated services	Not applicable

a Where funds are allocated to multiple resource groups, equal distribution is assumed

Table 6.5 (continued)

Departments		Directorates and sub-programmes	Expenditure routes and allocation[a]
National annual expenditure on environmental issues	Water Affairs and Forestry	Water resource assessment	Water resources R 98 333 556.17
		Integrated water resource planning	Water resources R 54 931 475.13
		Water resource development	Water and land resources R 258 359 072.76
		Integrated water resource management	
		• Water quality management	Water and land resources R 24 066 981.09
		• Catchments management	Water resources R 6 449 792.00
		• Working with water	Water resources R 12 510 835.29
		• Water utilisation	Water resources R 40 960 367.36
		• Water conservation	Water resources R 16 343 553.85
		Regional implementation	Water resources R 2 575 006 052.08
		Water services	Water resources R 74 580 701.43
		Forestry	Land resources R 396 966 612.84
	Agriculture	Farmer support and development	Not applicable
		Agricultural trade and business development	Not applicable
		Agricultural research and economic analysis	Not applicable
		Agricultural production	Not applicable
		Sustainable resource management and use	
		• Water use and irrigation development	Water resources R 61 606 154.51
		• Scientific research and development	Water and land resources R 865 268.05
		• Land use and soil management	Land resources R 76 020 310.65
		• Agricultural Research Commission	Air, water and land resources R 319 884 014.41
		• Others	Not applicable
		National agricultural regulatory services	Not applicable
		Agricultural communication, planning and evaluation	Not applicable

a Where funds are allocated to multiple resource groups, equal distribution is assumed

6.3 Weighting value results for the resource groups

The survey and AHP procedure makes two major assumptions: a random sample is obtained from the industry sectors, and the weights assigned by the participants are normally distributed [187]. The probability of inclusion of every company in each sector is not known to achieve a random sample. However, as the survey was circulated throughout the industry sectors, it is believed that the responses are representative of the industry sectors at decision-making or management level. In terms of the normality, the Kolmogorov-Smirnoff test was conducted on the obtained weights from the participants [212]. Table 6.6 shows that at a level of significance of 0.05 the obtained weights follow a normal distribution.

Table 6.6: The Kolmogorov-Smirnoff test for normality

Resource groups	Managing Director (automotive sector) D Max for n=43	Financial Directors (process industries) D Max for n=13
Air resources	0.088	0.159
Water resources	0.149	0.304
Land resources	0.114	0.227
Mined abiotic resources	0.198	0.240

H_0: The weights generated follow the normal distribution

H_1: The weights do not follow the normal distribution

$D_{.05,\ n=43} = 0.207$

$D_{.05,\ n=13} = 0.377$

The statistical distributions of the relative weights (AHP methodology) obtained from the individual judgements of Managing directors in the automotive supply chain and Financial directors in the process manufacturing industry are shown in Figures 6.2 and 6.3. The figures also show the percentages of the environmental expenditures of the national government that is allocated to the respective resource groups.

Geometric mean weighting values for the resource groups were obtained from the AIP combination method results of the two industry groups [210]. From the confidence level calculations, it could be estimated with 95% certainty that the average values are those shown in Table 6.7.

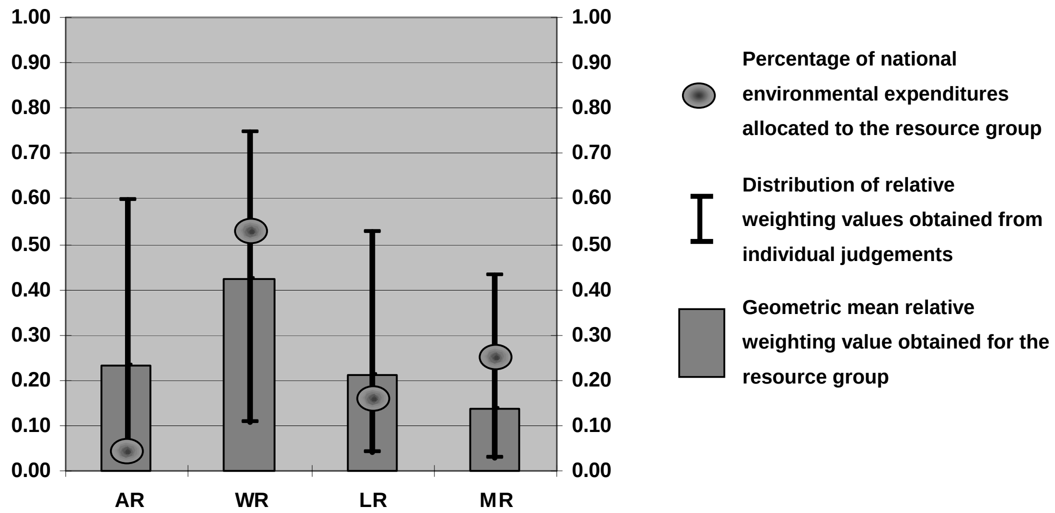

Figure 6.2: AHP survey and national expenditure results for the resource groups (Managing Directors in the automotive supply chain)

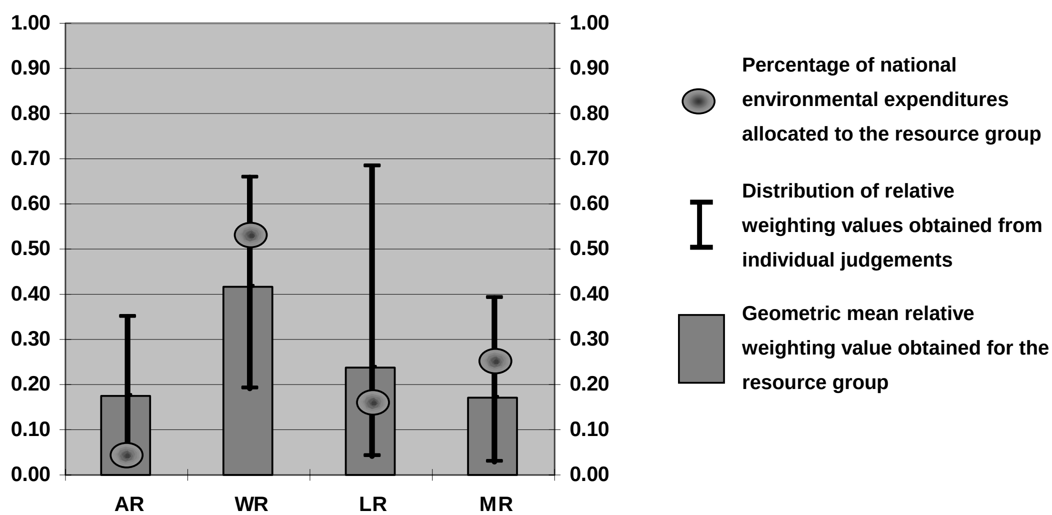

Figure 6.3: AHP survey and national expenditure results for the resource groups (Financial Directors in the process manufacturing industry)

Table 6.7: Geometric mean values of the AIP combination methods of the relative weighting values obtained from two manufacturing industry sectors

Sustainable development criteria	Geometric mean weighting value	95% confidence interval values
Air resources	**0.202**	0.165 to 0.239
Water resources	**0.420**	0.371 to 0.468
Land resources	**0.224**	0.189 to 0.259
Mined abiotic resources	**0.154**	0.119 to 0.189

6.3.1 Established subjective weighting values for South Africa

The subjective weighting values for the natural resource group were aggregated from the industry AHP survey results and the distribution of the expenditure allocation of the South African national government on environmental issues (see section 6.2.4). These are shown in Table 6.8.

Table 6.8: South African subjective weighting values for the resource groups

Representatives	Water resources	Air resources	Land resources	Mined resources
Managing directors: automotive supply chain	0.42	0.23	0.21	0.14
Financial directors: process manufacturing industry	0.41	0.18	0.24	0.17
National government expenditure trends	0.53	0.04	0.17	0.26
Average weighting values	**0.47**	**0.12**	**0.20**	**0.21**

6.4 Applying the EPRII methodology for supply chain management

The importance of evaluating the environmental performances of suppliers in Life Cycle Management (LCM) is discussed in Section 1.4.3 of Chapter 1. Complex products, such as an automobile, reflect the environmental burdens and economic beneficiation of an Original Equipment Manufacturer (OEM) and its suppliers. The former is under increased global pressure to compare and select suppliers with the least overall environmental impact per supplied product. A South African automobile

OEM has subsequently indicated the necessity to evaluate and compare the environmental performances of its first-tier suppliers [84]. However, environmental impacts data are typically lacking from within the supply chain and the environmental performances are currently based on limited process parameters, i.e. energy and water usage, and solid waste produced. Furthermore, these process parameters do not reflect the actual impact of company practices on the South African natural environment. Based on the obtainable process parameters from companies in the supply chain [84] and the LCIA model of Chapter 5, RII values can be calculated for suppliers, which are an improved indication of the true environmental burdens of supplier operations.

Figure 6.4 illustrates the required framework to calculate appropriate RIIs. It is thereby required to establish detailed Life Cycle Inventories (LCIs) for the process parameters except for water and raw energy material (natural gas, oil and coal) usage, which are assumed to be extracted directly from available surface and groundwater reserves in the regions (water) and obtainable reserves (raw energy materials). The detailed LCIs determine the extent of environmental impacts on the midpoint categories of using energy and producing solid waste. The following LCIs were subsequently compiled:

- Electricity usage (per MJ), based on available electricity generation data [136], and available European LCI data [134].
- Steam usage (per kg), based on available onsite steam generation data [137], and available European LCI data [134].
- Liquid fuel usage (per kg of diesel), based on adapted data from available diesel production databases [135].
- Solid waste produced (per kg), based on disposal at a medium-sized hazardous landfill site that operates in accordance with the guidelines and legislation of the South African national government [141].

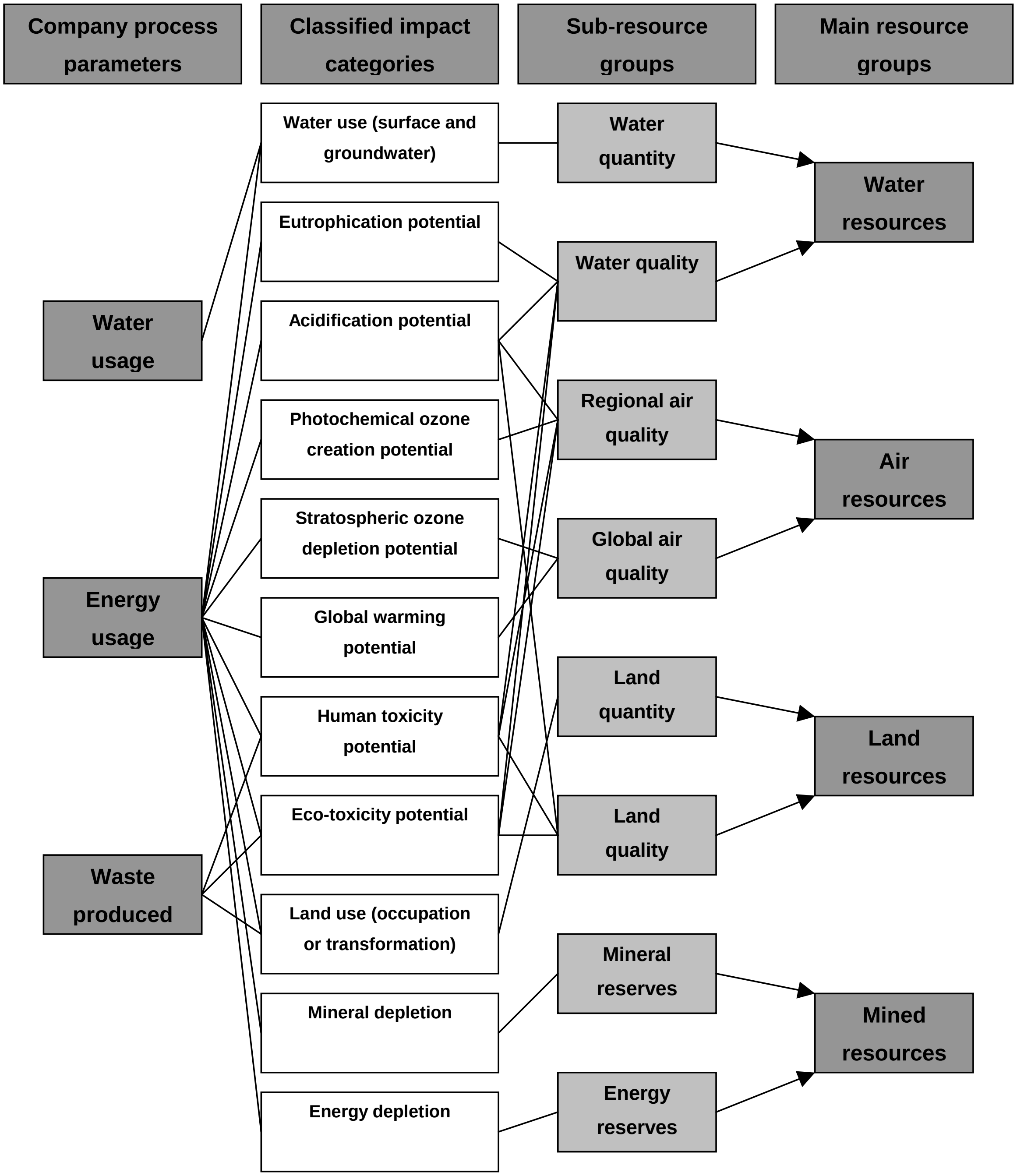

Figure 6.4: Framework to calculate the RIIs from obtainable process parameters

6.4.1 Solid waste produced (per kg)

In South Africa, except for recycling, very little produced solid waste is treated (and disposed of) by means other than landfill treatment, e.g. by incineration. The national

Department of Water Affairs and Forestry (DWAF) regulates landfill operations according to the hazardous rating of the treated waste [141]. Thereby, the allowed emissions to groundwater reserves (as measured pollutant concentrations in the reserves) and land usage are set depending on the size of the operation and the level of hazardousness of the treated waste. Additional operational requirements, such as energy and water usage, and potential emissions to air are omitted from the DWAF documentation.

Based on discussions with the South African automobile OEM [84], it is assumed that the majority of waste (produced by the first-tier supplier) is not of a high hazardous rating and can be treated on an average South African landfill site. Appendix E provides the calculations whereby the potential volume of groundwater reserves affected and the land usage were determined per kilogram of waste treated on such a site, based on the DWAF documentation [141]. The volume of groundwater reserves was used to convert the allowed pollutant concentrations to masses for inventory purposes. The detailed inventory is given in Appendix F. By further assuming that the waste produced in a South African region is treated on an average landfill site in that region, and using the current and target ambient environmental state data for the regions with the modified LCIA model of Chapter 5, the associated RII values could be calculated per kilogram treated waste for the four SALCA Regions (see Table 6.9). The table also shows the RII results if South Africa were considered as one region.

Table 6.9: Calculated RII values per kg of solid waste treated

	SALCA Region 1	SALCA Region 2	SALCA Region 3	SALCA Region 4	South Africa
Water resources	5.072×10^{-7}	5.918×10^{-8}	3.529×10^{-7}	1.872×10^{-7}	4.719×10^{-8}
Air resources	1.312×10^{-11}	5.833×10^{-12}	4.076×10^{-12}	5.700×10^{-12}	1.506×10^{-12}
Land resources	2.557×10^{-8}	5.302×10^{-8}	8.591×10^{-8}	4.020×10^{-9}	2.730×10^{-8}
Mined abiotic resources	0	0	0	0	0

6.4.2 Electricity usage (per MJ)

The typical South African electricity mix is shown in Figure 6.5 [136]. The figure also shows the source of compiled inventory data for electricity usage. A detailed inventory database has been compiled for all of the electricity generation technologies [134]. In the case of coal thermal generation, the inventory has been updated with South African specific information from the major electricity utility Eskom [136]. The detailed LCI data is given in Appendix F.

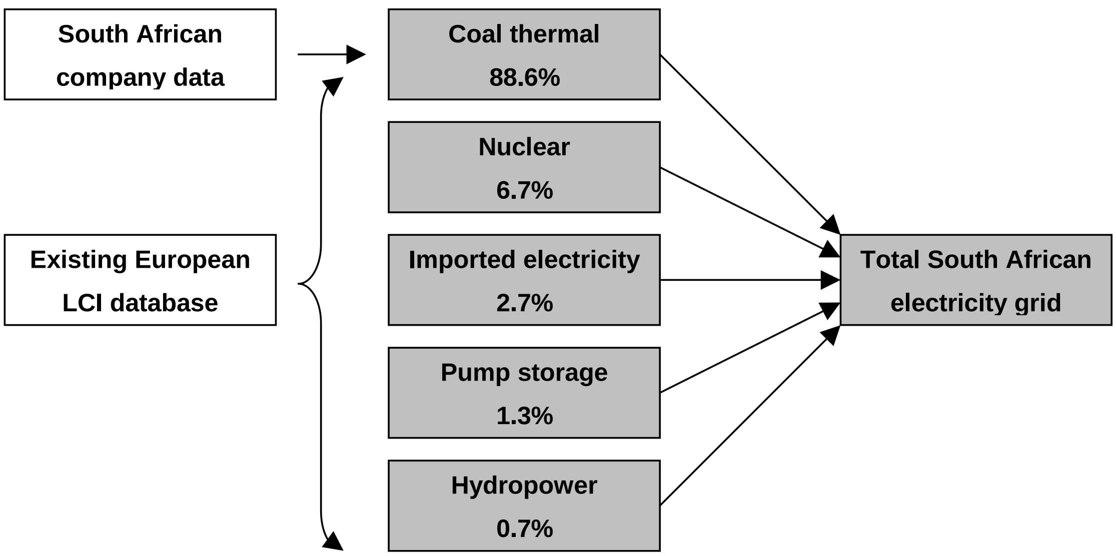

Figure 6.5: Source of LCI data for the South African electricity generation mix

The majority of South African electricity is generated in SALCA Region 3 [136]. Using the current and target ambient environmental state data for this region with the modified LCIA model of Chapter 5, the following RII values were calculated per mega joule of electricity used in any region of South Africa:

- Water resources - 4.523×10^{-3}
- Air resources - 1.026×10^{-4}
- Land resources - 9.650×10^{-7}
- Mined abiotic resources - 5.057×10^{-7}

6.4.3 Liquid fuel usage (per kg)

The manufacturing industry often uses liquid fuels during normal operations, e.g. to fire burners or for on-site generators. It is assumed that the South African industry primarily uses diesel as liquid fuel. Approximately a third of South African diesel is produced from coal, with the remainder from crude oil resources [213]. In the case of diesel production from coal, existing LCI databases [135] have been updated with company-specific data, i.e. Sasol [213]. European databases [134] were used for diesel manufacturing from crude oil resources (see Appendix F).

As with electricity, the diesel manufacturing from coal takes place in SALCA Region 3. However, the manufacturing facilities for diesel from oil resources are located in SALCA Regions 1 and 2. The overall inventory data was therefore incorporated with current and target ambient environmental state data for South Africa as a whole to calculate overall RII values for diesel usage (per kilogram) in any region:

- Water resources - 8.756×10^{-3}
- Air resources - 1.104×10^{-4}
- Land resources - 1.043×10^{-6}
- Mined abiotic resources - 1.683×10^{-5}

6.4.4 Steam usage (per kg)

The overall inventory data for steam usage per kilogram (Appendix F) was determined from actual measurements of on-site steam boilers at a number of industries in South Africa together with existing European LCI databases (see Table 3.4 of Chapter 3) [134, 137]. The actual environmental impact of the LCI is dependent on the region where an on-site boiler is in operation. Table 6.10 shows the RII values calculated per kilogram steam generated in the four SALCA regions and if South Africa is considered as one region.

Table 6.10: Calculated RII values per kg of steam generated on-site

	SALCA Region 1	SALCA Region 2	SALCA Region 3	SALCA Region 4	South Africa
Water resources	1.714×10^{-2}	8.292×10^{-5}	3.551×10^{-4}	1.922×10^{-4}	7.324×10^{-5}
Air resources	7.285×10^{-6}	2.395×10^{-6}	1.975×10^{-6}	2.729×10^{-6}	7.061×10^{-7}
Land resources	2.202×10^{-7}	2.337×10^{-8}	5.352×10^{-8}	3.202×10^{-8}	1.242×10^{-8}
Mined abiotic resources	4.283×10^{-7}	4.283×10^{-7}	4.283×10^{-7}	4.283×10^{-7}	4.283×10^{-7}

6.4.5 Water usage (per kg)

The impact of water usage is entirely dependent on the current and target groundwater and surface water reserve states in the different regions. The RII values calculated for water usage (per kilogram) are summarised in Table 6.11.

Table 6.11: Calculated RII values per kg of water used

	SALCA Region 1	SALCA Region 2	SALCA Region 3	SALCA Region 4	South Africa
Water resources	2.960×10^{-2}	4.551×10^{-5}	2.380×10^{-5}	1.945×10^{-5}	4.896×10^{-5}
Air resources	0	0	0	0	0
Land resources	0	0	0	0	0
Mined abiotic resources	0	0	0	0	0

6.4.6 Raw energy material usage (per kg)

Certain energy resources are directly used as raw materials in the manufacturing sector. The main resources that are included in this research are natural gas and coal. The impacts associated with the actual extraction and supply of these energy resources are excluded from a detailed LCI. Thereby only mined abiotic RIIs are determined per kilogram used of natural gas (4.955×10^{-6}) and coal (3.599×10^{-6}) in South Africa.

6.4.7 Environmental performances comparison of first-tier suppliers

The environmental performances of three first-tier suppliers to the automotive OEM in Pretoria were evaluated and compared with the EPRII methodology. The companies supply the OEM with fuel tanks, windscreens and tyres for a standard sedan vehicle. Table 6.12 provides an estimate of the process parameters that have been obtained for the companies per supplied component through personal interviews. The table also provides an estimate of the economic costs of the supplied components to the OEM.

Table 6.12: Process parameters obtained from the OEM's first-tier suppliers

	Fuel tank[a]	Windscreen[a]	Tyre[a]
Energy usage			
• **Electricity (MJ)**	63.7	60.5	234.1
• **Liquid fuel (diesel)(kg)**	0.0	0	0
• **Steam (kg)**	0.0	0	20.4
• **Raw energy materials (kg)**	0.0	2.0[b]	0
Water usage (kg)	4.6	176.8	20.5
Waste produced (kg)	0.1	32.0	1.0[c]
Economic cost (R)	1000.00	1460.00	500.00

a Process parameters are shown per supplied component.

b Natural gas for furnace operation.

c 10% assumed losses.

All of the first-tier suppliers are located in SALCA Region 3 in close vicinity to the OEM's manufacturing facility. The associated RII values for each company per supplied component are summarised in Table 6.13.

Table 6.13: RII values calculated for the three manufactured components

	Fuel tank[a]	Windscreen[b]	Tyre[c]
Water resources	2.882×10^{-1}	2.779×10^{-1}	1.067×10^{0}
Air resources	6.535×10^{-3}	6.206×10^{-3}	2.406×10^{-2}
Land resources	6.148×10^{-5}	6.113×10^{-5}	2.271×10^{-4}
Mined abiotic resources	3.222×10^{-5}	4.051×10^{-5}	1.271×10^{-4}

a Electricity usage per manufactured fuel tank contributes more than 99% to all of the calculated RIIs.

b Electricity usage per manufactured windscreen contributes more than 98% to all of the calculated RIIs.

c Electricity usage per manufactured tyre contributes more than 99% to all of the calculated RIIs.

In order to compare the environmental performances of the first-tier suppliers equally (from an OEM perspective), the RII values must further be normalised with the monetary costs of the components [84] (see Figure 6.6), i.e. the RII values are given per supplied Rand (ZAR) cost and the associated indicators can be compared evenly. Figure 6.7 compares these normalised RII values for the three components.

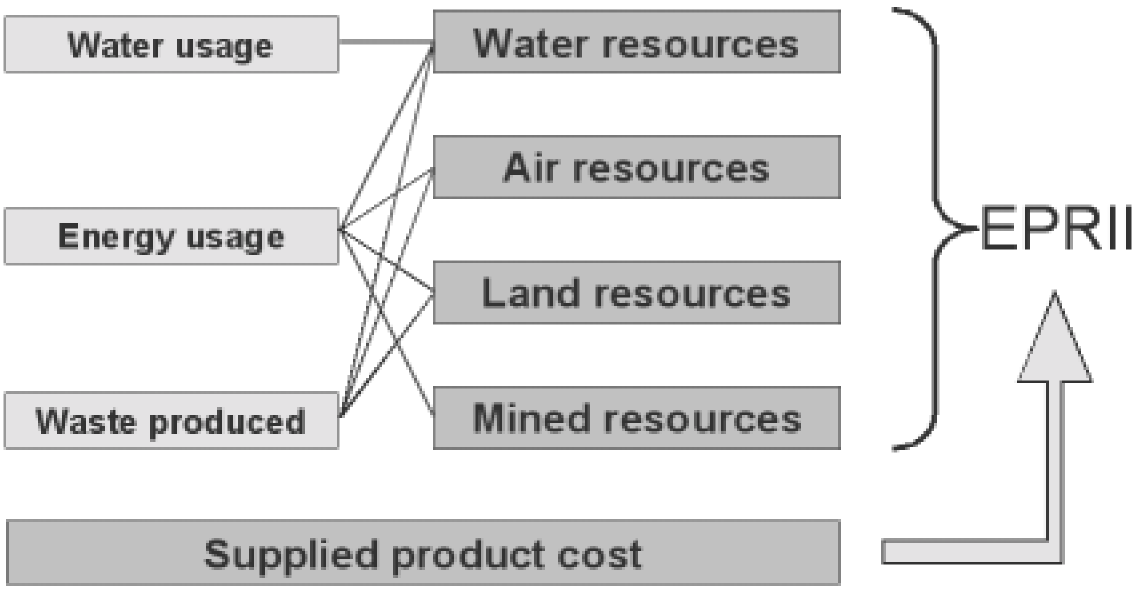

Figure 6.6: Calculated EPRII value per supplied product cost for an OEM

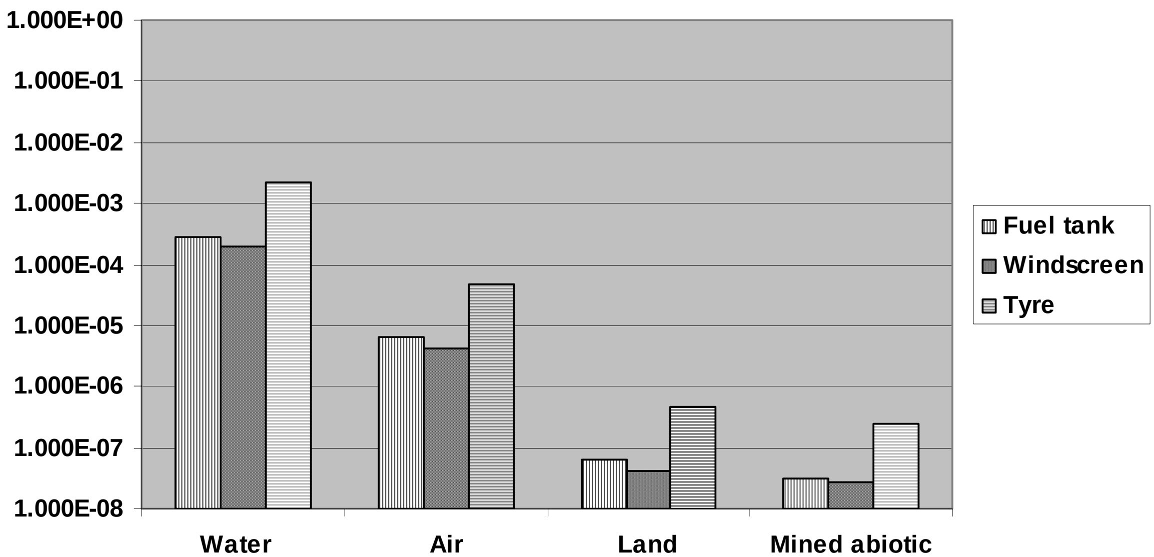

Figure 6.7: RII values for the three supplied components per supplied cost

Applying the RII calculation procedure to evaluate the environmental performances of the first-tier suppliers shows that electricity usage is the most important process parameter (see Table 6.13). This parameter has an impact on all of the midpoint categories. However, the burdens on water resources are the highest. The impacts on the water resources are primarily attributable to the Acidification Potential, Human Toxicity Potential and Aquatic Toxicity Potential midpoint categories. The ambient environmental state in SALCA Region 3, which is used for (distance-to-target) normalisation purposes, therefore signifies these categories to be the most important for the electricity LCI.

The EPRII approach, introduced in Section 6.1, was further applied together with the established subjective weighting values for the four resource groups stipulated in Table 6.8, to compare the overall environment performances of OEM supplying companies. Per economic cost, the EPRII procedure prioritises the suppliers of tyres to receive attention in terms of improving environmental performances, followed by the fuel tank. The ranking procedure and subjective weighting values of the four resource groups do not influence the outcome of the environmental performances evaluation and comparison (for these first-tier suppliers). This is due to large contribution of electricity usage to the calculated (total) RIIs for all three of the first-tier suppliers. If different process parameters (between compared suppliers) are important in terms of influencing calculated RIIs, the same RII profile will not be observed and the ranking procedure and subjective weighting values would consequently be required for an overall comparison of the suppliers. For example, the manufacturers of certain metallic components often use high quantities of liquid fuel, which also has a high impact on all of the resource groups (see section 6.4.3).

The sensitivities of the results to the costs of the components have been tested and are shown in Figure 6.8 (for the Water RII only). The supplied tyre is the most sensitive to the cost thereof to the OEM. However, the cost itself would not influence the overall outcome of the EPRII procedure significantly.

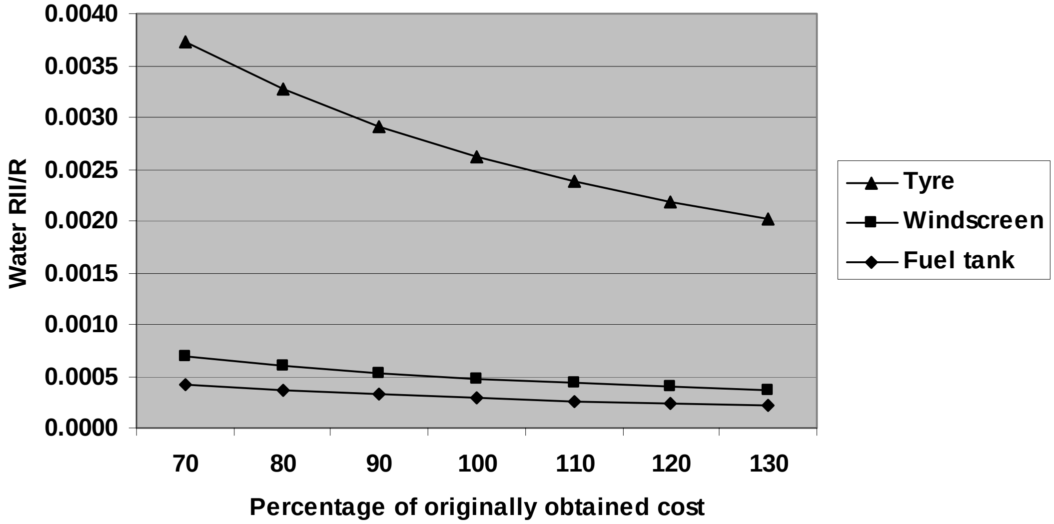

Figure 6.8: Sensitivity of the Water RII with the costs of the components

6.5 Conclusions

This chapter introduces an Environmental Performance Indicator (EPI) approach for Life Cycle Management (LCM) purposes. The Environmental Performance Resource Impact Indicator (EPRII) procedure compares the calculated Resource Impact Indicators (RIIs) of life cycle systems qualitatively. Thereafter subjective weighting values for the four natural resource groups are applied to determine an overall single environmental performance score for one life cycle system compared to another. These subjective weighting values are established from the perspectives of decision-makers or managers in the South African automotive manufacturing value chain, and the expenditure of the national government on environmental issues.

The chapter further demonstrates the application of the EPRII procedure through the quantitative evaluation of the overall environmental performances of three first-tier supplier companies of a South African automotive Original Equipment Manufacturer (OEM). These suppliers manufacture fuel tanks, windscreens and tyres for the OEM. The monetary costs of the supplied components are incorporated into the evaluation process. Normalising the environmental burdens of supplier activities with the economic costs of the supplied components provides a means to equally compare the burdens at an operational level, i.e. environmental performances (of the supply chain) can be linked to expenditure trends (of an OEM assembly facility). However, this is not an indication of the total environmental burdens associated with the final product (see Figure 1.14 of Chapter 1). This is exemplified in the automotive supply chain case study:

- The supplied tyre has the highest overall environmental burden per Rand spent (in the order of a factor of 10 compared to the fuel tank and windscreen). However, a supplied tyre has an economic value of half to a third compared with the fuel tank and windscreen, and the ratio difference between environmental burdens associated with the complete components would therefore be smaller. Conversely, for the specific studied sedan, five tyres are supplied per manufactured automobile, which would increase the environmental burdens (and total cost to the supplier) by a factor of five.
- The manufacturing activities of the first-tier suppliers were considered only, as is the current case in the South African automobile manufacturing sector. Second- and subsequent tiers would have to be included to obtain an indication of the overall environmental burdens, although the economic cost of the components to the OEM would not change. This has proven to be difficult for tiers that are further away from the OEM, especially for smaller companies in South Africa and where secondary components are imported.

From the perspective of an automotive product system, the EPRII procedure should rather reflect the environmental burdens associated with the final assembled product. Thereby OEMs would be provided with the means to obtain a first approximate of environmental concerns in the supply chain (per manufactured product), based on three basic process parameters: water and energy usage, and solid waste produced. Tiers can subsequently be prioritised to determine where assistance is required to improve environmental performances.

Chapter 7: Conclusions and recommendations

The main contributions of the research project to the fields of LCA and LCM are summarised in Table 7.1. The main results of the research are recapitulated below the table and elaborated on in the main sections of this chapter (Sections 7.1 to 7.4).

Table 7.1: Main contributions of this research project

Contribution	Detailed contributions
A new South African Life Cycle Impact Assessment (LCIA) procedure, termed the Resource Impact Indicator (RII) method	• Grouping of environmental impacts in terms of four natural resource groups as Areas of Protection (AoP), in order to simply environmental reporting • Introducing characterisation factors for land use in South Africa for future LCIAs • Defining South African LCA regions that better reflect impacts on the diverse local ecosystems, without being too site-specific • Setting normalisation and grouping values for the defined regions (and impact categories), based on ambient environmental data • Introducing a calculation procedure to quantify the total environmental impacts of systems on the natural resource groups
A qualitative and quantitative evaluation and comparison of the existing and the developed South African LCIA procedures	• Indicating the necessity for Life Cycle Inventories (LCIs) and LCIAs to be spatially differentiated • Highlighting other impact categories (and LCIA procedures) that must be addressed in the South African context • Identifying key environmental impacts associated with certain life cycle systems in the South African manufacturing sector
The establishment of subjective weighting values for the South African LCIA procedure	• Establishing weighting values for the four natural resource groups of the South African LCIA procedure • Introducing a procedure to evaluate and compare the overall environmental performances of systems
Application and integration of the South African LCIA procedure to solve Life Cycle Management (LCM) problems in the context of the South African manufacturing industry	• Identifying the problems associated with improving the environmental performances of supply chains • Modifying the LCIA procedure framework to evaluate and compare suppliers in the South African manufacturing sector • Compiling a software application for RII calculations in industry

With respect to the developed RII procedure for South Africa in Table 7.1, ambient current and target state values were established for the midpoint categories that contribute to four natural resource groups: water, air, land, and mined abiotic resources (see Table 7.2 and section 7.1 below for a detailed discussion). Based on these ambient current and target values normalisation factors were determined for the midpoint categories through the known distance-to-target methodology. The normalisation values (for South Africa as one region) are summarised in Table 7.2, and also determine the relative importance of each midpoint category to a resource group if South Africa is considered as one region. Characterisation values for LCI constituents that contribute to the midpoint categories are given on a website [169].

Table 7.2: Normalisation and weighting values for the RII procedure

Midpoint category		Normalisation value[a]	Resource group	Weighting value
Water Usage	– kg available reserves	6.511×10^{-5}	**Water**	0.47
Eutrophication Potential	– kg PO_4^{3-} equivalence	1.648×10^{-5}		
Acidification Potential	– kg H_2SO_4 equivalence	6.249×10^{-6}		
Human Toxicity Potential	– kg Pb equivalence	2.665×10^{-2}		
Aquatic Toxicity Potential	– kg Pb equivalence	2.665×10^{-2}		
Acidification Potential	– kg SO_2 equivalence	5.449×10^{-4}	**Air**	0.12
Ozone Creation Potential	– kg O_3 equivalence	4.019×10^{-5}		
Ozone Depletion Potential	– kg CFC-11 equivalence	1.261×10^{-7}		
Global Warming Potential	– kg CO_2 equivalence	1.208×10^{-13}		
Human Toxicity Potential	– kg Pb equivalence	5.207×10^{-5}		
Acidification Potential	– kg H_2SO_4 equivalence	6.249×10^{-6}	**Land**	0.20
Human Toxicity Potential	– kg Pb equivalence	2.267×10^{-7}		
Terrestrial Toxicity Potential	– kg Pb equivalence	2.267×10^{-7}		
Occupied Land Usage	– m^2.a near-natural	3.955×10^{-5}		
Transformed Land Usage	– m^2 non-natural	1.695×10^{-4}		
Mineral Depletion	– kg Pt equivalence	5.615×10^{-6}	**Mined Abiotic**	0.21
Energy Depletion	– kg coal equivalence	3.599×10^{-6}		

a Values calculated for South Africa as whole; for separate SALCA Regions the values in Appendix D are used with the equation C_S/T_S^2 (see equation 5.1 of Chapter 5)

The current LCIA procedures that are used in the South African manufacturing industry were qualitatively evaluated in terms of the main elements of the LCIA phase of LCAs, i.e. characterisation, normalisation and weighting. The LCIA procedures were thereafter quantitatively compared with the developed RII procedure with a compiled life cycle system, i.e. the production of dyed two-fold wool yarn in South Africa. The main results of the analyses are summarised in Table 7.3 and discussed further in section 7.2.

Table 7.3: Results of the analysis of the different LCIA procedures

Method	Qualitative analysis	Quantitative analysis[a]
CML	The consequence of impacts on human health and ecosystems are not considered. A comprehensive list of midpoint categories is listed in the documentation, but are not all functional yet. The normalisation step does provide a choice for region-specificity. No weighting mechanism is proposed.	Land use is indicated to be the most important LCI parameter. However, no formal modelling values are currently introduced for this category. If land use is not included, the air emissions (in the wool life cycle) are shown to be the most important LCI constituents.
Ecopoints	The consequence of impacts on human health and ecosystem quality is considered during the normalisation and distance-to-target weighting step. The included midpoint categories are not comprehensive. The modelling of the categories is region-specific.	The solid waste (from coal burning) to produce energy is shown to be most important constituent in the wool life cycle. However, the consistency of the normalisation values is questioned.
Eco-indicator 95	The modelling procedure does consider the consequences of impacts in the three LCIA steps. The method is not comprehensive in terms of the considered categories, or region-specific. The weighting step does include a significance factor, which is an improvement over the conventional distance-to-target approach.	A number of environmental categories are highlighted as important in the wool life cycle, but are all associated with steam production, electricity generation and transport requirements.
Eco-indicator 99	The method follows a definite endpoint approach. The only category (of the conventional categories) that is missing in the South African context is water usage. The method is not region-specific. The weighting applies a panel approach, but with an improvement over conventional panel methodologies.	Land-use is indicated to be the most important environmental category in the wool life cycle. However, the impact modelling is based on specific vegetation types in the Netherlands and may not be appropriate for South Africa.
EPS	No normalisation step is included in the method, but the characterisation and weighting steps do consider the endpoint consequences of impacts. The incorporated midpoint categories are comprehensive, and the method has a region-specific approach. The weighting step applies the willingness-to-pay principle, which may be problematic in the South African context.	Water and land usage are shown to be the most important LCI constituents. However, the results are based on the calculation of monetary Environmental Load Units (ELUs), which may not be appropriate for South Africa. The final indicators are therefore not dimensionless.
RII	The consequences of impacts are considered in the setting of normalisation values. All conventional midpoint categories are duly considered for the four main natural resource groups. Region-specificity is also introduced in the setting of normalisation/grouping values in the South African context.	The impacts on water, air, land and mined abiotic resources are evaluated separately and compared thereafter. For the wool life cycle, the impacts on water (usage) and land (usage) resources are the largest.

a For the production of 1kg of dyed two-fold yarn wool in South Africa.

Subjective weighting values were obtained for the four main natural resource groups from a South African perspective. Individual judgements of decision-makers (or managers) in the manufacturing sector were used with the Analytical Hierarchy Process (AHP), a known decision-analysis technique. The expenditure trends of the national government on environmental issues were further used as an indication of the relative importance that is placed on the four resource groups by the South African society. An aggregate value was determined (see Section 7.3), which is also summarised in Table 7.2.

The subjective weighting values are used in an Environmental Performance Resource Impact Indicator (EPRII) approach, which can be applied for specific LCM problems, e.g. to evaluate the environmental performances of suppliers (see Section 6.4). For this purpose RII values were required for the limited process parameters that can typically be obtained from within South African supply chains. Table 7.4 provides the RII values for the most important process parameters (if South Africa is considered as one region). The overall RIIs (for the water, air, land, and mined abiotic resource groups) for a process or company are determined through the summation of all the RII values of the obtained process parameters.

Table 7.4: RII values[a] for selected process parameters

Process parameter[b]		Water Resources	Air Resources	Land Resources	Mined Abiotic Resources
Waste produced	- 1 kg	4.719×10^{-8}	1.506×10^{-12}	2.730×10^{-8}	0
Electricity used	- 1 MJ	4.523×10^{-3}	1.026×10^{-4}	9.650×10^{-7}	5.057×10^{-7}
Liquid fuel used	- 1 kg	8.756×10^{-3}	1.104×10^{-4}	1.043×10^{-6}	1.683×10^{-5}
Natural gas used	- 1 kg	0	0	0	4.955×10^{-6}
Coal used	- 1 kg	0	0	0	3.599×10^{-6}
Steam used	- 1 kg	7.324×10^{-5}	7.061×10^{-7}	1.242×10^{-8}	4.283×10^{-7}
Water used	- 1 kg	4.896×10^{-5}	0	0	0

a These values are for the whole of South Africa. RII values for activities in specific SALCA Regions are given in sections 6.4.1 to 6.4.6 of Chapter 6.

b The correlation between the process parameters and related RII values is linear.

The EPRII approach further applies a simple ranking value procedure that assigns a qualitative impact value of 1, 0, and –1 to the resource groups, based on the RII performance of one system compared to another (termed baseline) for each natural resource group. A value of 1 therefore indicates a better environmental performance of one system compared to the baseline (for a specific resource group); -1 a worse performance; and 0 indicates no significant difference in the calculated RII values for the systems. Subjective weighting values for the resource groups are used to calculate an overall single score for a system, which is a comparison with the baseline or reference system.

Finally, the RII calculation procedure is provided through a user-friendly software application at the end of this chapter. Apart from comparing the results of the developed LCIA procedure with existing procedures for the wool and other product life cycles, the user is presented with a 'RII calculator' to compute overall RII values for life cycle systems for which only limited process parameters are available. The application and installation instructions are given on a website [214].

Figure 7.1 summarises the process that was followed in this research project.

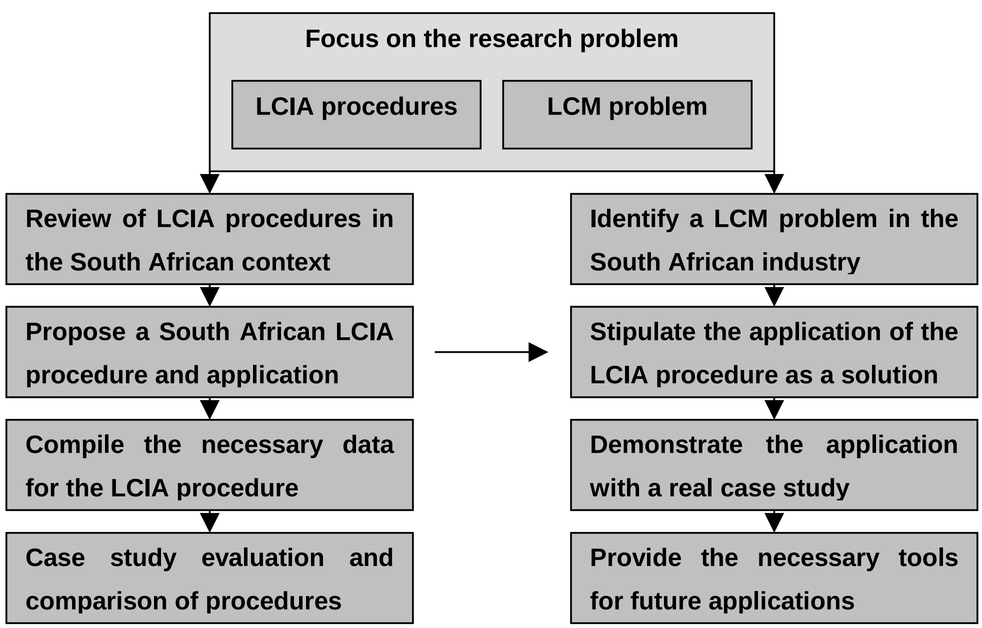

Figure 7.1: Research process to solve the research problem

7.1 An LCIA procedure from compiled South African environmental data

A framework is proposed whereby the Life Cycle Impact Assessment (LCIA) phase of a comprehensive Life Cycle Assessment (LCA) can be performed for decision-support purposes in the South African manufacturing industry. The framework was compiled using environmental sciences data that were available in South Africa (at the beginning of 2002 as a first approximate), and which are appropriate within the scope of typical LCIA methodologies that have been developed internationally. The framework also complies with the ISO 14042 standard for the LCIA phase of LCAs and includes the elements shown in Figure 7.2.

The Resource Impact Indicators (RIIs) that are calculated through the framework aim to provide a simpler means to equally compare the impacts of a life cycle system on four natural resource groups: water, air, land and mined abiotic resources. These resource groups are specifically addressed by the South African constitution and when evaluating the impacts associated with South African industries. The impact indicators on water, air and land resources take into account the current and target ambient burdens on human health and ecosystem quality in four defined regions, termed SALCA regions. The mined abiotic resource indicators consider the current and projected mineral and energy reserves at a national level, and are therefore not region-specific.

It must be noted that the RII framework oversimplifies the complexity of the environmental science disciplines in terms of reporting environmental impacts. The framework does, however, ensure that the most relevant environmental criteria of an evaluated system are considered, and a singular criterion may be indicated to have the dominant influence on a resource group.

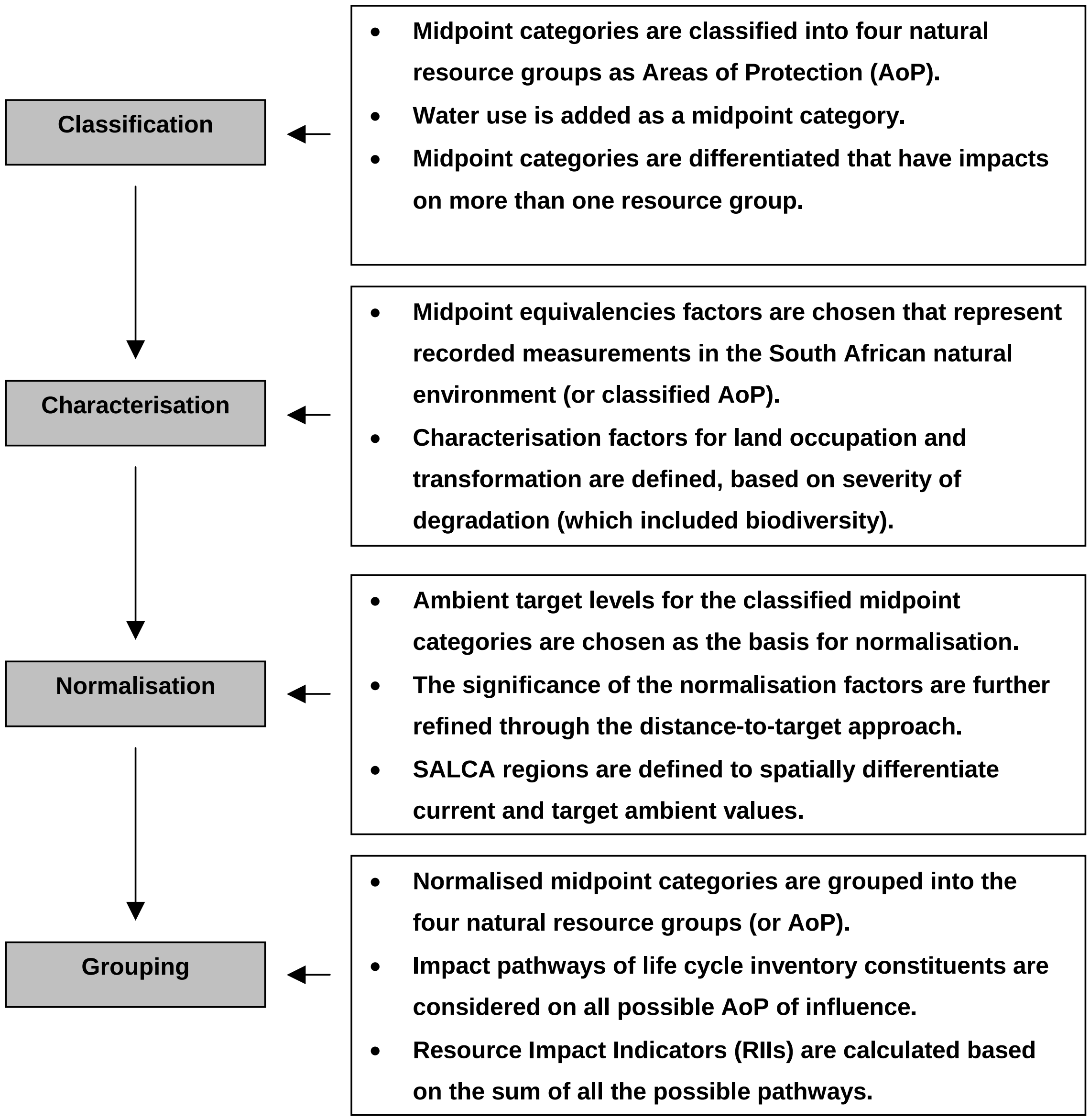

Figure 7.2: Elements of the proposed South African LCIA procedure

The components of the RII framework must be investigated in greater detail from the perspective of natural environmental sciences disciplines, and specifically:

- The exhaustiveness of the classified impact categories. Certain categories that are important in the South African context, e.g. salinity of fresh water, are currently omitted from the framework. These should be included if appropriate for an evaluated system.

- The applicability of the characterisation modelling approaches for each of the current impact categories, and the development of characterisation models for newly introduced impact categories. For example, there is currently no differentiation between the use of water from surface and groundwater reserves in the characterisation step. Also, the use of degradation severities is proposed for the characterisation of land use, but should be confirmed by expertise in the field. Furthermore, specific industrial impacts, e.g. acid mine drainage, do not receive adequate attention in the characterisation of the current classified categories.
- The current and target state values used in the normalisation and grouping elements of the LCIA phase. Certain South African datasets are currently limited to use in the RII approach. For example, the current acidification states of South African soils have been worked on [165], but the data have a high uncertainty and target levels are not known at this stage. Similarly, the trace elements data that have been used in this study has a high level of uncertainty and is currently (as at the beginning of 2003) under further investigation [165]. A more scientific basis for the spread of the ambient concentrations across the SALCA regions is also required, and the conversion from concentrations to ambient annual mass values (required for LCIAs) is of particular concern.

Furthermore, the implications of changes in the legislation of South African on the RII procedure must be considered. Increasing knowledge and understanding of environmental impacts leads to the revision of environmental policies and regulation criteria. These, in turn, would influence the target values that are used in the RII procedure.

7.2 Comparison of the different LCIA procedures

The relevance and practicality of use of the proposed RII procedure in the context of typical LCA studies were investigated with a quantitative comparison to other LCIA methodologies. Although, in some cases, the chosen impact categories differ between the current published methods, the classification generally follows a list of categories that have been described [87]. The categories classified by these methodologies have been grouped into air, water, land and mined abiotic resources, for comparison purposes with the RII procedure. Air, water and land are sub-divided still further into the characteristic human health and ecosystem quality criteria. These criteria are taken into account by these procedures either in the characterisation phase (CML, Eco-indicators 95 and 99, and EPS) or in the setting of target values for weighting purposes (Ecopoints and Eco-indicators 95).

Air pollution problems, especially human health impacts are dealt with in detail by all the methods. Impact categories and procedures relating to air pollution and human health are typically applicable in South Africa. However, care must be taken where exposure modelling is included in a LCIA procedure because meteorological conditions that usually influence results can vary. Similarly, dose-response modelling could be erroneous because of the different cultural lifestyles of South African communities (e.g. diet, reliance on home-grown food, etc). Similarly, human health impacts due to water quality reduction could also be applied in South Africa, although many communities use natural water systems without pre-treatment, as is the case in Western Europe.

The relevance of the methodologies is reduced when categories are used to indicate potential impacts to ecosystem quality. Ecosystems differ significantly between South Africa and the European continent. Although these methods address ecosystem quality to some degree for water and air pollution, the comprehensiveness of these categories varies considerably. Also, water quantities are only taken into account by one European method (EPS). This is problematic because water quantities are very important in a dry country such as South Africa. To a certain degree, the impact of land use and soil emissions on ecosystem quality is also incorporated into some of the procedures (CML, Eco-indicator 99 and EPS). However, the combination of demand for agricultural land, mismanagement and erratic climate conditions mean that biodiversity conservation is under strain in South Africa [10]. The incorporation of this impact category is therefore important in the South African context.

Depletions of mined abiotic resources, i.e. minerals and energy, are not localised impacts, although the depletions may be of concern at a national level. Therefore the European LCIA procedures are probably adequate for life cycle evaluation purposes in South Africa. However, the national government may place a high value on these resources because of their contribution to South African export revenue [11]. This could mean that a higher weighting value for these resources is appropriate.

The normalisation and weighting principles of the European LCIA procedures could also be unrealistic when applied to the South African situation. Normalisation of all the procedures, except EPS (no normalisation), requires background emissions and mined abiotic resource use data. This kind of background data is difficult to collect in South Africa and does not necessarily reflect the environmental burdens of economic activities on the resource groups. With respect to the particular weighting mechanisms the following can be deduced:

- Distance-to-target methodology: the scientific and policy values used might not be applicable in South Africa.
- Panel methodology: the cultural preferences in South Africa differ significantly from those in Europe.
- Willingness-to-pay methodology: other sustainability criteria (socio-economic and economic) outweigh environmental aspects and parts of society may not deem the environment to be economically important.

Apart from social and economic differences, environmental conditions in South Africa vary significantly from the European continent [10]. This means that applying LCIA procedures that have been developed for Europe without adjusting them for South African conditions is likely to be problematic. In particular, attention must be given to the environmental criteria of water and land, which, from a South African perspective, are very important. The RII procedure therefore specifically incorporates these resources.

The wool manufacturing industry of South Africa was used for the quantitative comparison of the LCIA methodologies. The scope and inventory data of the screening life cycle study have certain limitations that could influence the interpretation of the LCIA results, which should be addressed in a detailed LCA, for example:

- Only one eco-region was considered for the sheep-farming step in the manufacturing process, which represents 26% of all sheep-farming regions in South Africa (SALCA Region 1). The eco-systems that are characteristic of this region are highly sensitive with a consequent low grazing capacity. Sheep farming in the other regions will subsequently have a lower impact in terms of land use and could lower the importance of this impact category. Also, the water consumption of sheep in different eco-regions will vary and influence the impact on the water use midpoint category.
- A detailed LCA would include additional inventory parameters for the sheep farming, e.g. methane release from the sheep. The pesticide administration assumptions should also be investigated further for South Africa as this release to the ambient environment has significant local impacts.
- Only Merino sheep were included in the inventory of the sheep-farming step, which comprises 50% of the total sheep population of South Africa. The nutritional demands of other sheep breeds would influence the land use and supplement demands.
- The actual releases of chrome dyes into South African water sources must be investigated in greater detail, which is the largest impact on water quality in the manufacturing step. Similarly, the wastewater treatment at the manufacturing facilities, as well as the treatment of solid waste, must receive more attention.

The wool case study, however, was adequate to demonstrate the reporting of impact indicators on the four natural resource groups. Additional South African case studies are required to determine the use of these indicators at decision-making level. In this respect further research in the South African resources industry has been initiated.

With respect to the specific environmental burdens associated with the wool screening LCA case study, Table 7.5 shows the three highest priorities that are given by the five commonly used LCIA procedures in South Africa and the developed RII procedure.

Table 7.5: Environmental impact categories prioritised by the LCIA procedures

LCIA procedure	Priority 1	Priority 2	Priority 3
CML	Land use	Abiotic depletion	Global warming potential
Ecopoints	Waste (solid emissions)	Sulphur oxides emissions	Carbon dioxide emissions
EI95	Pesticide emissions	Acidification potential	Heavy metals
EI99	Land use	Respiratory inorganic emissions	Climate change
EPS	Biodiversity	Drinking water	Human life (fatal)
RII	Water use	Occupied Land Use	Human Toxicity Potential

Table 7.5 shows the inconsistencies of the environmental impact categories that are highlighted as the most important for the wool case study. Where land use is introduced as a specific category, it is indicated to be the most important for the case study. Similarly, water use is a specific category in one current LCIA procedure (EPS), and is evaluated as the second most important environmental burden associated with the production of wool in South Africa. The largest resemblance in the outcomes of the different LCIA procedures is between the Scandinavian EPS and the developed RII procedure. However, the RII procedure places a higher priority on the use of water as a resource in South Africa.

The developed RII procedure further reports only four indicators on water, air, land and mined abiotic resources. The number of categories, which are to be considered by decision-makers, is therefore reduced and the indicators directly address the environmental aspects that are emphasised by South African regulators. The four indicators have been used to quantitatively compare the placement of the wool production life cycle in the four defined SALCA Regions of South Africa. The results show that placing the wool life cycle in any other region would be better (from an environmental perspective), compared to the current SALCA Region 1. Therefore, by applying the RII procedure to the wool screening LCA case study it is shown that a spatially differentiated approach influences the results of the LCIA and also affects the quantification of LCI constituents, especially with respect to land and water usage.

7.3 Subjective weighting values for the four natural resource groups

An Environmental Performance Indicator (EPI) approach is further introduced, to compare the performance of one LCI system to another in terms of calculated RIIs. Subjective weighting values for the four natural resource groups are used to calculate an overall single score or Environmental Performance Resource Impact Indicator (EPRII). The judgements of representatives (managing directors and financial directors) from two industry sectors (manufacturing and process) in the South African automotive value chain were used to determine relative weighting values with the Analytical Hierarchy Process (AHP). The results indicate a similar spread of responses between the two industry sectors, and an average weighting value could be determined from an industry perspective. As a further indication, the expenditure trends of the national government on environmental issues were considered to obtain overall weighting values for the four resource groups (see Figure 7.3). However, the values are not necessarily representative of individual opinions in government departments, non-government organisations, academia and businesses not included in the manufacturing sectors. In particular, the view of the multicultural South African society that is affected by industrial activities must be evaluated. Such an attempt has been made before [203], but was unsuccessful due to communication barriers (the concepts of environmental burdens on society is ill understood by many South Africans). Additional personalised workshops will be required to obtain a representative perspective by the different South African cultural groups, and other sectors.

A single score EPRII is most applicable for internal decision-making purposes. It would therefore be beneficial to investigate the internal subjective weights that are placed on the four natural resource groups. Research is ongoing to determined these weighting values at:

- Government level: The Clean Development Mechanism (CDM) secretariat has been newly established in the South African government to oversee the trading of Global Warming gases as part of the Kyoto Protocol. It is the responsibility of this secretariat to evaluate potentially eligible projects in terms of overall sustainability for South Africa. In addition to weighting values of sustainability criteria (including the four natural resource groups), thresholds are considered.

Thereby, certain categories would be prioritised. Only if no impacts were shown on these categories would a further detailed evaluation proceed.

- Industry level: The South African process industry is currently developing a sustainability framework to evaluate projects internally, which includes the four natural resource groups. Total Cost Assessment and Multi Criteria Decision Analysis methodologies will be applied to determine weighting values for a petrochemical industry.

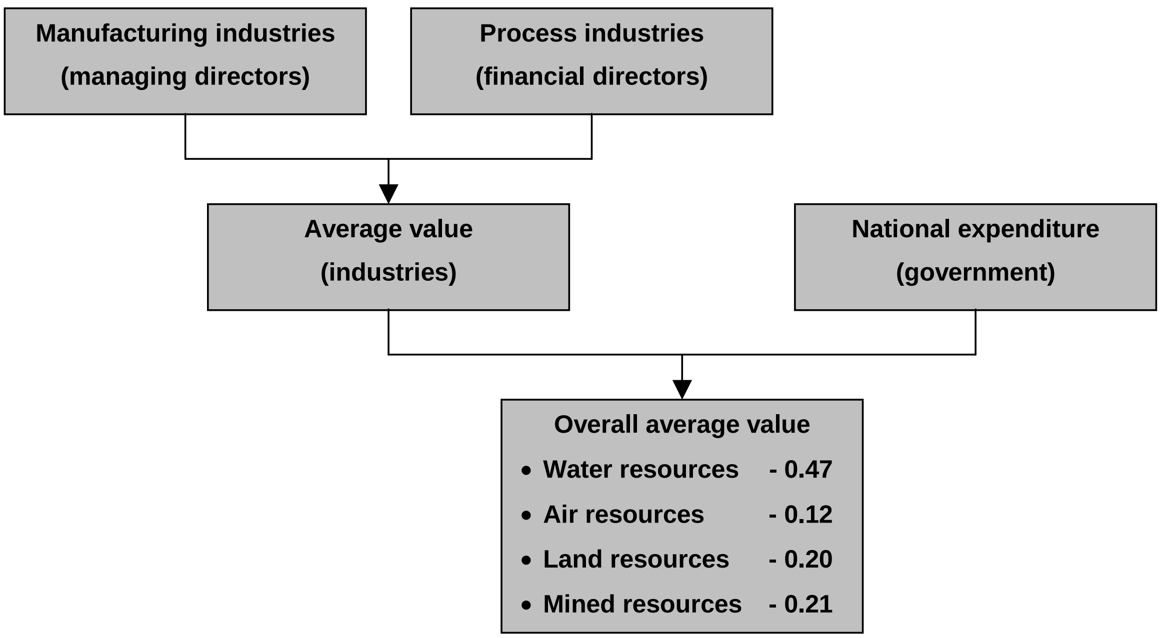

Figure 7.3: Determining South African weighting values for the resource groups

7.4 Application of the EPRII procedure to a South African LCM problem

Environmental Management Systems (EMS) are increasingly pressurised to focus on the supply chain of global market products. This is especially true for OEMs, and suppliers in the automotive value chain are compelled to adhere to certain standards set by customers. The South African manufacturing sector contributes progressively more to the global automotive market and local suppliers understand the need to conform to these international practices. From a sustainable development perspective for OEMs, however, a responsible and transparent approach is required to assess the environmental impacts associated with products imported from South Africa.

This research suggests that an environmental evaluation should be region-specific in a South African context, whereby additional stresses of a product supply system is determined on current water, air, land and mined resources qualities for four SALCA regions. It is further proposed to incorporate the economic cost of the supplied components into the evaluation process (see Figure 7.4).

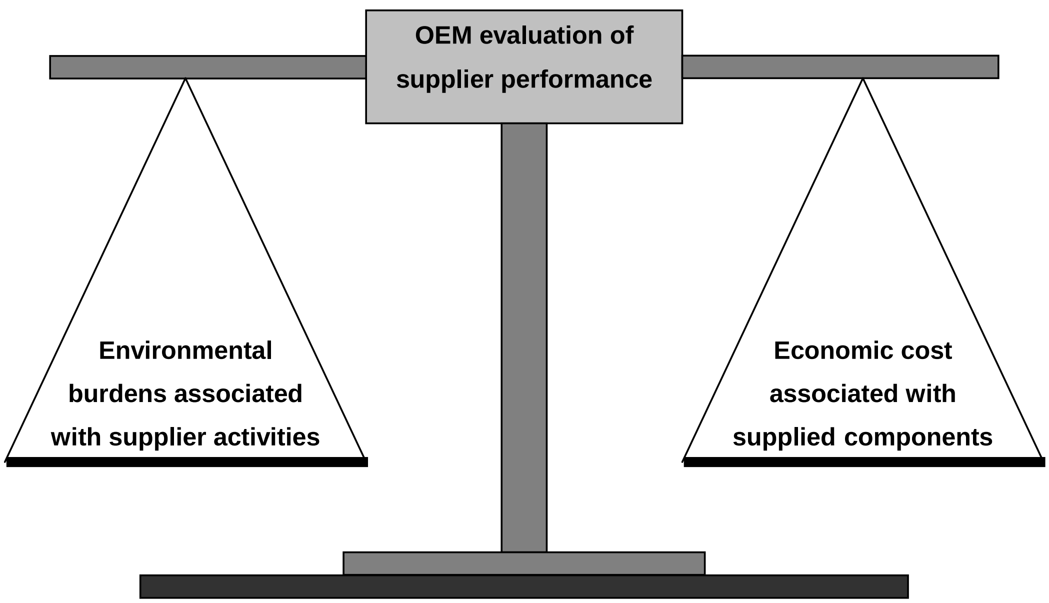

Figure 7.4: Environmental and economic considerations for supplier evaluation

Normalising the environmental burdens of supplier activities with the economic value of the supplied components provides a means to equally compare the burdens. However, this is not an indication of the total environmental burdens associated with the final product (see Figure 1.14 of Chapter 1). This is demonstrated in an automotive supply chain case study, where the environmental performances of three first-tier suppliers of a South African OEM were evaluated and compared (see Section 6.5 of Chapter 6). These companies supply the OEM with fuel tanks, windscreens and tyres for the assembly of standard sedans.

The EPRII procedure provides the means for OEMs to obtain a first approximate of environmental concerns in the supply chain, based on three basic process parameters: water and energy usage, and waste produced. Thereby, tiers can be prioritised to determine where assistance is required to improve environmental performances. Research has commenced to study the supply chain of one OEM in South Africa in greater detail, where the EPRII tool will be used.

The EPRII approach could similarly be applied in project and asset management disciplines (see Sections 1.4.1 and 1.4.2 of Chapter 1) where detailed data are often too limited to base substantial environmental evaluations on. In South Africa this is especially true during the design stages of technologies in the process manufacturing industry [68].

7.4.1 Software application to assist with RII evaluations as part of the EPRII procedure

A Java application has been compiled to simplify the RII determination of systems in a standalone format, which is downloadable from the internet [214]. The application consists of existing life cycle systems (to compare the results of the different LCIA procedures) and an RII calculator, which computes the impacts on the four natural resource groups based on limited process parameters. Figure 7.5 highlights the main components of the application. Appendix G presents some screen shots of the application. Appendix H provides the description of the code of the software.

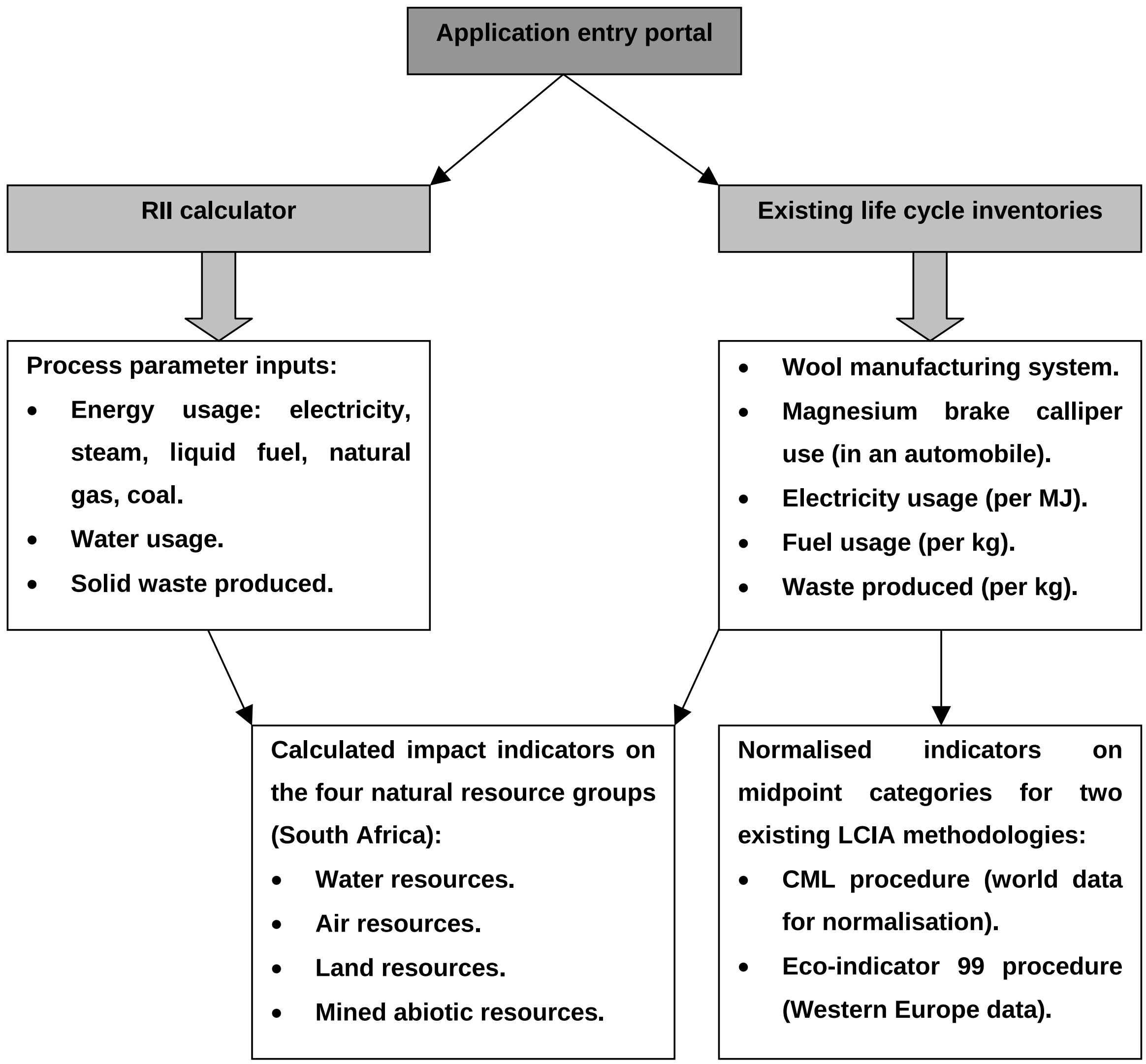

Figure 7.5: Components of the compiled Java application

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