LCA Methodology with Case Study

Comparative Evaluation of Life Cycle Impact Assessment Methods with a South African Case Study

Alan C. Brent[1]* and Sibbele Hietkamp[2]

[1] Chair: Life Cycle Engineering, Department of Engineering and Technology Management, School of Engineering, University of Pretoria, South Africa
[2] Environmental Process Solutions, Process Technology Centre, M&Mtek, CSIR, South Africa

*Corresponding author (abrent@eng.up.ac.za)

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Abstract

Goal and Background. LCIA procedures that have been used in the South Africa manufacturing industry include the CML, Ecopoints, EPS and Eco-indicators 95 and 99 procedures. The aim of this paper is to evaluate and compare the applicability of these European LCIA procedures within the South African context, using a case study.

Methods. The five European methods have been evaluated based on the applicability of the respective classification, characterisation, normalization and weighting approaches for the South African situation. Impact categories have been grouped into air, water, land and mined abiotic resources for evaluation purposes. The evaluation and comparison is further based on a cradle-to-gate Screening Life Cycle Assessment (SLCA) case study of the production of dyed two-fold wool yarn in South Africa.

Results and Discussion. Where land is considered as a separate category (CML, Eco-indicator 99 and EPS), the case study highlights this inventory constituent as the most important. Similarly, water usage is shown as the second most important in one LCIA procedure (EPS) where it is taken into account. However, the impact assessment modelling for these categories may not be applicable for the variance in South African ecosystems. If land and water is excluded from the interpretation, air emissions, coal usage, ash disposal, pesticides and chrome emissions to water are the important constituents in the South African wool industry.

Conclusions. In most cases impact categories and procedures defined in the LCIA methods for air pollution, human health and mined abiotic resources are applicable in South Africa. However, the relevance of the methods is reduced where categories are used that impact ecosystem quality, as ecosystems differ significantly between South Africa and the European continent. The methods are especially limited with respect to water and land resources. Normalisation and weighting procedures may also be difficult to adapt to South African conditions, due to the lack of background information and social, cultural and political differences.

Recommendations and Outlook. Further research is underway to develop a framework for a South African LCIA procedure, which will be adapted from the available European procedures. The wool SLCA must be revisited to evaluate and compare the proposed framework with the existing LCIA procedures.

Keywords: Applications; life cycle assessment (LCA); life cycle engineering (LCE); life cycle impact analysis (LCIA); limitations; methods; problems; procedures; South Africa

Introduction

Life Cycle Engineering (LCE) is a decision support tool that incorporates data about economic and environmental aspects with an evaluation of the technology, for use in the design phase [1]. **Fig. 1** illustrates the integrated approach that brings together financial, environmental and technical aspects in the decision process and the tools used to evaluate these aspects. South Africa is in many respects unique where sustainable development is concerned [2].

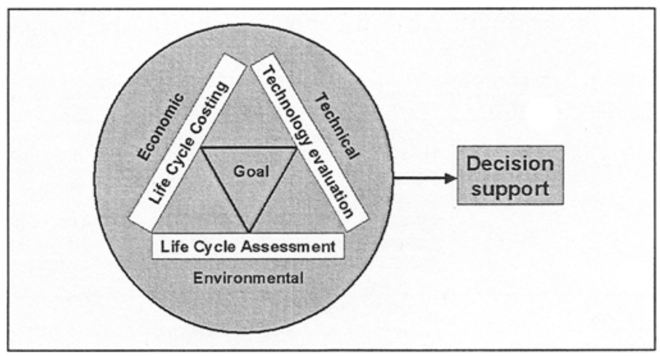

Fig. 1: The decision support mechanism of Life Cycle Engineering [1]

The requirements pertaining to sustainability in South Africa must be understood for local LCE evaluations and decision support in terms of:

- **Economic considerations**; the need to increase the export potential of South Africa whilst addressing the needs of the local consumer market and socio-economic sustainability.
- **Technical considerations**; technologies that address the needs of the South African society and its sustainability in a global marketplace.
- **Environmental considerations**; pressures experienced from economical and technological developments due to the unique ecological characteristics of South Africa.

The latter emphasises the need to ensure that the Life Cycle Impact Assessment (LCIA) procedure used in the Life Cycle Assessment (LCA) component of LCE addresses South African conditions.

The complexity of the LCIA procedure lies in the cause-effect chains linking emissions and resource dissipation to the consequences [3]. These cause-effect chains show that environmental impacts can be described at different levels

of effects. Because of the complexity of evaluating the cause-effect chain of each environmental impact, LCA practitioners and software packages use published LCIA methods. As an example, the following European based LCIA procedures have been used in South Africa for decision support in the manufacturing sector [4]:

- CML from Leiden University, the Netherlands [5].
- Ecopoints from BUWAL, Switzerland [6].
- Eco-indicators 95 [7] and 99 [8] from Pré Consultants, the Netherlands.
- EPS from Chalmers University of Technology, Sweden [9].

Although these LCIA approaches differ [10], they do comply with the basic requirements as set out by the TC207 technical committee of ISO [11]. The ISO 14042 standard stipulates what is to be considered when executing the obligatory elements (classification and characterisation), whilst the optional elements dependent on the application. For example, when a product comparison is done and the results are to be presented to the general public, weighting should not be used [11]. 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 [12]. As LCE implies an evaluation in the design stages, the optional elements of the five abovementioned LCIA procedures, and especially normalisation and weighting, must also be considered in the South African context. Grouping of impact categories and weighting usually have a political or social element that influences the weighting values. Three weighting procedures that are in common use have been proposed [13]:

- The **panel method**: a panel of individuals ranks the importance of various impacts. The relative weight of each impact depends on the chosen panel.
- The **monetary method**: an economic cost is placed on the environmental damage caused by an impact.
- The **distance-to-target method**: the difference between current levels of environmental impacts and target levels set by LCA practitioners is used, which are typically based on government policy.

The aim of this paper is to evaluate and compare the applicability of the five LCIA procedures that have been used in the South African manufacturing sector for design and decision purposes [4], on a qualitative and quantitative basis. The qualitative evaluation is based on the applicability of the classification, characterisation, normalization and weighting approaches for Design for Environment (DfE) purposes in the South African situation, considering the social, cultural and political differences, as well as the spatial conditions in general. The approaches of the LCIA procedures have been obtained from available documentation [5, 6, 7, 8, 9], and are summarised in **Table 1**. For the quantitative evaluation and comparison a screening LCA case study is performed, which is based on a Life Cycle Inventory (LCI) covering a 'cradle to gate' perspective of wool production in South Africa.

Table 1: Summary of classification, characterisation, normalisation and weighting approaches [5–9]

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)

The wool industry in South Africa. At the turn of the century, the agricultural sector contributed 4.1% of the national Gross Domestic Product (GDP) of South Africa [14]. For the last five years agricultural products have contributed approximately 8%, on average to total exports. Of the 1.5 billion US$ revenues generated from agricultural exports in 2000, roughly 2% were attributable to the export of wool fibres [15]. Although the contribution of wool to the national economy is small, the industry is still regarded as important. In terms of world production, South Africa is the sixth largest producer of this product, i.e. 3 to 4% (33,000 tonnes) [16,17]. The significance of the environmental impacts of wool production needs to be assessed in the South African context.

1 Goal and Scope of the Wool Screening Life Cycle Assessment (SLCA) Case Study

1.1 Allocation of environmental impacts within the South African wool industry

South Africa has a wool-producing sheep population in the order of 20 million [18,19], i.e. half of the human population, of which more than 10 million are located in the Western Cape, Eastern Cape and Northern Cape Provinces. The Nama Karoo Biome comprises the largest vegetation type in this region [20]. Less than one percent of this biome is protected and this may in part be due to the high land usage requirement from farming activities and the low grazing capacity associated with these eco-regions [21]. The rainfall in this region is also low with most areas receiving less than 400 mm per year. Consequently, the management of the natural resources, i.e. water and land (and soil erosion), has received much attention [21,22]. These resource constraints have resulted in the number of sheep farming activities remaining fairly constant. In the case of certain sheep species, some of the environmental impacts related to the farming activities should be allocated to meat products. However, with the Merino sheep (50% of all sheep), wool constitutes the primary produce and the impacts are allocated solely to this product.

The downstream or post-farming life cycle stages of wool production have also received considerable attention [23]. The primary environmental concerns are associated with the release of polluted wastewater from the textile processes [16]:

- 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 affected include the Biological Oxygen Demand (BOD), Total Suspended Solids (TSS) and concentrations of oils from the wool fibres [24]. In some cases acidic waste streams are treated with lime, which necessitate the disposal of waste solids. Additional environmental impacts include air emissions from the use of energy for steam production and electricity supply, although these have not obtained much attention. Allocation of impacts within the wool production process is required between wool fibres, and by-products such as short fibres (noil) and wool grease [25]. These by-products do not have the economic value of the wool fibres used for shrink-resist treatment, spinning and dyeing, and the allocation is therefore based on the mass ratio of the different products.

1.2 The purpose of the wool case study

The production of wool has an environmental effect on air, water, land and mined abiotic resources. This wide range of impacts makes the production of wool in South Africa a good case study to evaluate and compare the quantitative results of each Life Cycle Impact Assessment (LCIA) procedure.

1.3 The functional unit of the wool case study

The functional unit of the life cycle case study is 1 kilogram of dyed two-fold wool yarn. The life cycle system to produce this functional unit is divided into two primary processes and a number of 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.
- 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 dyeing.

Transport is required to send the fleece from the wool farms to the industrial processes, and then again to the spinning mill after shrink-resist treatment of the wool. Auctioning of the greasy wool takes place before the wool is industrially processed.

1.4 System boundaries for the wool case study

The actual use and final disposal of the dyed two-fold yarn is not included. The life cycle study is therefore a cradle-to-gate assessment of the pre-manufacturing stages of wool production in South Africa.

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 [26]. 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 [27]. 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 excluded if it has an energy ratio of less than 0.05 compared to the whole system. It should be noted that problems have been associated with cut-off procedures in life cycle studies [28]. However, for the simplified SLCA 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 farming activities, the environmental burdens of classing and shearing with mechanical hand pieces, which are still the common practice, are not large and are therefore not taken into account in this case study. Similarly, the impacts associated with the auctioning of the wool have not been considered.

2 Inventory of the Wool Life Cycle Case Study

2.1 Process diagram

A simplified process diagram of the life cycle of 1 kg of dyed wool yarn is shown in Fig. 2.

2.2 Data gathering

2.2.1 Sheep farming

The majority of the data collected for sheep farming practices was 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.

2.2.2 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.

2.3 Data quality

Data quality can be analysed in terms of validity (i.e. the degree to which it is representative of the life cycle system) and reliability (i.e. the completeness, variability and uncertainty of the data) [29]. Although the data is representative of the life cycle system, the reliability is problematic. Sheep farming practices vary according to the specific eco-regions of South Africa. For example, the resource-use for wool production 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 to some degree from those in developed countries and significant uncertainty existed where data from international publications were used.

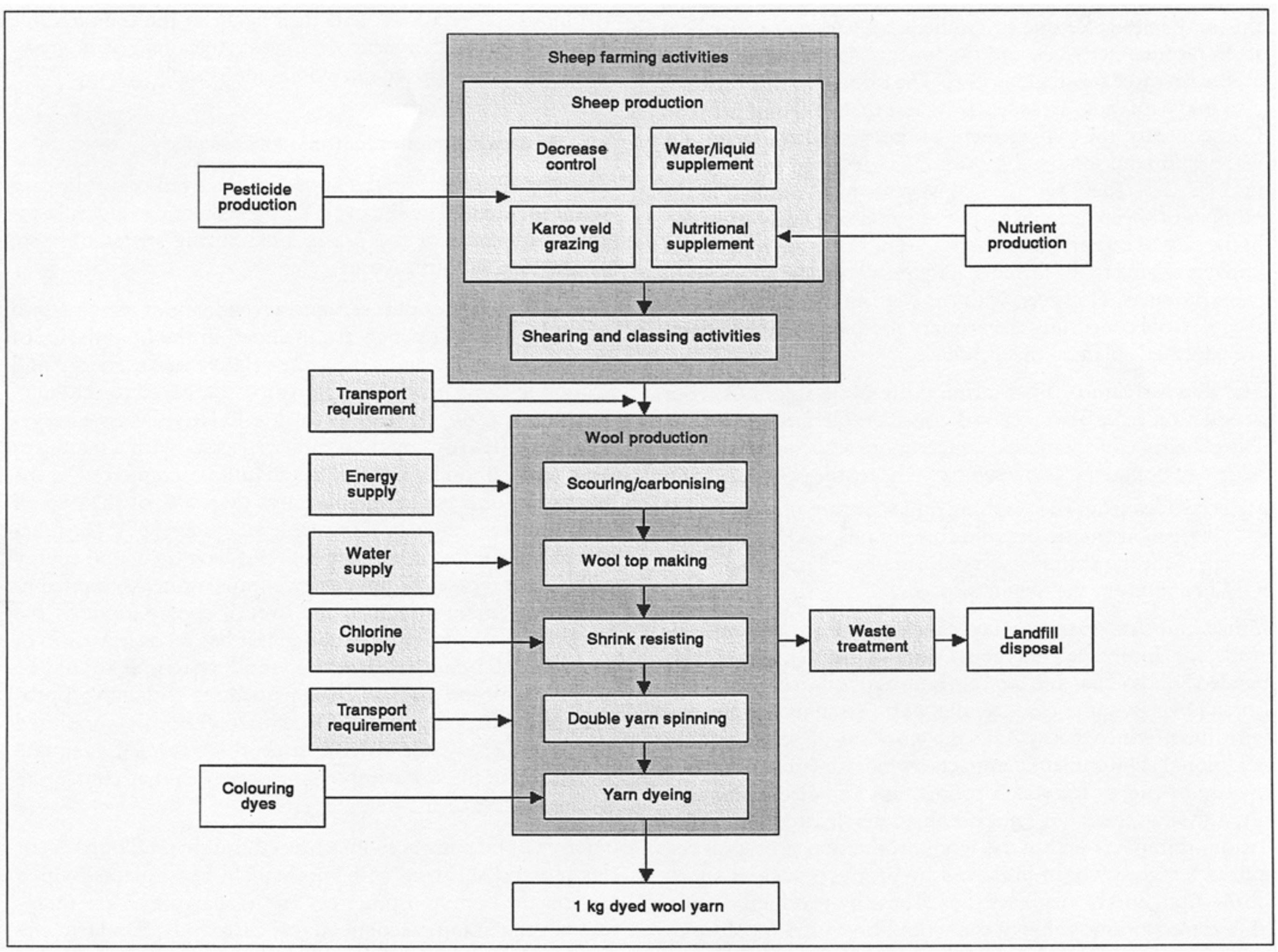

Fig. 2: The life cycle of 1 kg dyed wool yarn in South Africa. Shaded areas: processes included in the boundaries of the life cycle system. Non-shaded areas: processes not included in the boundaries of the life cycle system

2.4 Omitted data

The following unit processes have been omitted from the life cycle system (see Fig. 2):

- Pesticide production. The costs of pesticides are significant in terms of the RMEE method so they 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 are included in the case study.
- Nutritional supplement production. The cost of food supplements is significant. The environmental burdens associated with these production processes are not considered to be 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. Except for chlorine and epichlorohydrine, the RMEE method excludes these materials from the study, e.g. dyes, detergents, acids, etc. However, the 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 quality drinking water for processing are excluded from the case study. In a detailed study this data would need to be collected for each municipality.
- 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 [30]. 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, the release of pollutants from properly managed disposal sites are presumed to be less than the direct process releases to the ambient environment.
- 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.

2.5 Inventory data

The values of the data obtained for the unit processes have been altered to reflect the functional unit and are summarised in **Table 2**. The input and output constituents of the unit processes are determined by calculation from the gate (bottom of the table) to the cradle farming activities (top of the table). Wastewater from the scouring and shrink-resist processes of Table 2 is treated in on-site evaporation ponds. These have also been included within the boundaries of the study. The wastewater effluent from the dyeing process is discharged directly into surface water sewage systems.

The most important constituents that describe the interaction between the unit processes included in the life cycle system (see Fig. 2 and Table 2) and nature are given in the LCI profile of **Table 3**.

Table 2: Dyed two-fold yarn reference flows considered in the case study

		Constituent	Value	Unit	Comments and references for calculated values
Wool farming	Inputs	Karoo veld (land)	10247	m^2	28500 m^2 per sheep producing 4 kg fleece [21,31,32]
		Water (drinking)	453	kg	1.26 t/yr/sheep sheared twice annually for 2 kg [22]
		Maize supplement	8.09	kg	22.5 kg/yr/sheep producing 4 kg fleece [22,33,34]
		Lucerne supplement	8.09	kg	22.5 kg/yr/sheep producing 4 kg fleece [22,33,34]
		Pesticides	3	g	2 g/kg fleece [35,36,37,38]
	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 [39]
	Output	Greasy wool[b]	1.97	kg	40% loss during scouring and carbonising [37]

Table 2: Dyed two-fold yarn reference flows considered in the case study (cont'd)

			Constituent	Value	Unit	Comments and references for calculated values
Wool production	Scouring [16,24,40,41,42,43,25]	Inputs	Electricity	0.2	MJ	40 kWh at 80% efficiency for 500 kg/hr [44,45]
			Steam	12.25	kg	Allocation based on production rate [46,44]
			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[a]	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 [16,37,25]	Inputs	Electricity	0.02	MJ	0.5 kWh at 80% efficiency for 100 kg/hr [44,45]
			Steam	4.98	kg	Allocation based on production rate [46,44]
			Lubricants/antistatic	0.01	kg	1% of main unit process product
		Output s	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[a]	0.09	kg	7.5% of processed wool
Wool production	Shrink-resist treating [37,42]	Inputs	Electricity	0.22	MJ	25 kWh at 80% efficiency for 360 kg/hr [44,45]
			Steam	5.33	kg	Allocation based on production rate [46,44]
			Freshwater	7.63	kg	7 l/kg of processed wool
			Cl_2	0.18	kg	2% solution for 3000 l [44]
			Na_2SO_3	0.045	kg	0.5% solution for 3000 l
			Epichlorohydrine	0.18	kg	2% solution for 3000 l [44]
			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 [39]
		Output	Shrink proofed wool	1.08	kg	7% product lost in the spinning process
Wool production	Spinning [37, 41]	Inputs	Electricity	0.308	MJ	22 kWh at 80% efficiency for 206 kg/hr [44,45]
			Steam	7.16	kg	Allocation based on production rate [46,44]
			Lubricants	0.01	kg	1% of unit process product
		Output	Two-fold yarn	1	kg	No weight gaining during dyeing
	Dyeing [24, 41]	Inputs	Freshwater	30	kg	30 l/kg of wool produced
			Steam	4.46	kg	Allocation based on production rate [46, 44]
			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

[a] Impacts of upstream processes are allocated separately for noil by-product
[b] Impacts of upstream processes are allocated separately for greases

Table 3: 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

[a] LCI value calculated per 1 kg of dyed two-fold yarn product

[b] Occupied as existing arable land

3 Life Cycle Impact Assessment (LCIA) Results

Table 4 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 was compiled by evaluating the relative contribution of the LCI profile to the elements of the LCIA profile. 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. Fig. 3 is an example of the classification and characterisation LCIA results using the CML procedure.

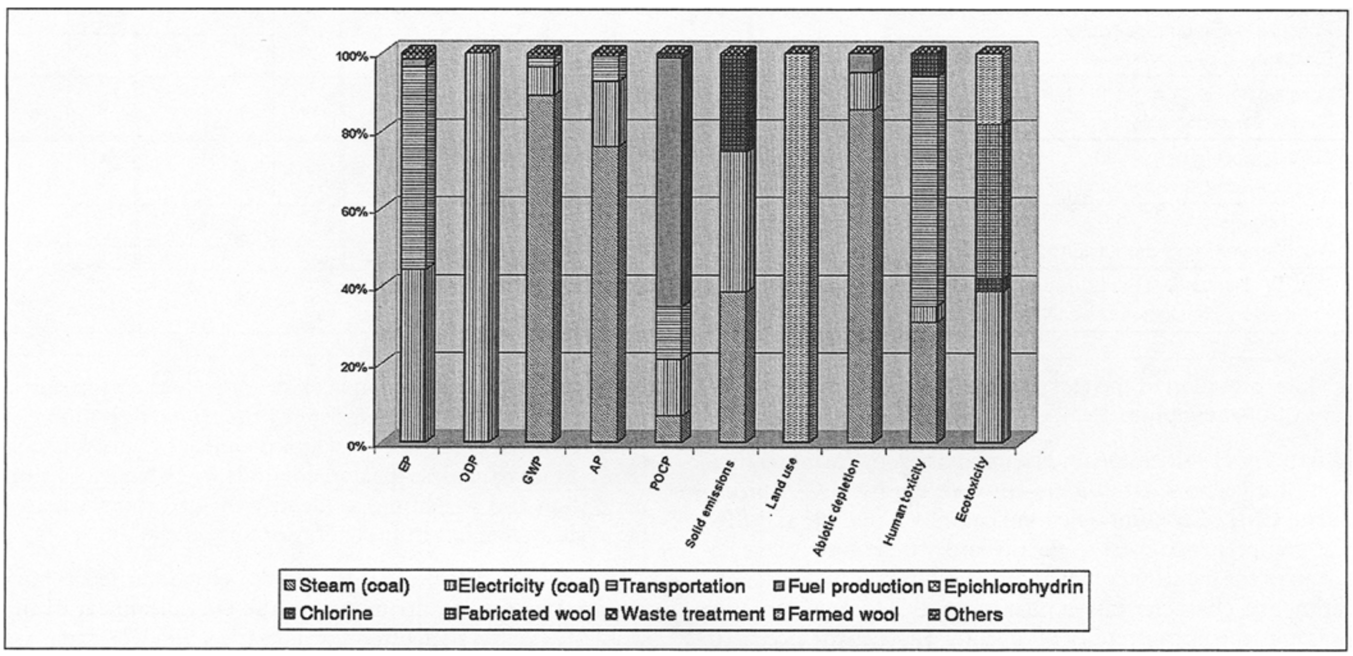

Fig. 3: Classification and characterisation results using the CML LCIA procedure

Table 4: Comparison of important inventory data that influence the 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 (and classification), normalisation and weighting
✓: Inventory constituent is significant to the element of the LCIA procedure

4 Interpretation of the Results and Comparison of LCIA Procedures

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 a 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 have been identified as having a meaningful contribution to the overall impact of the wool life cycle system after normalisation and weighting are shown Table 5.

Table 5: Relative importance of inventory 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

A ranking value has been 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:

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

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

From Table 5, 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 [6,7]. 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 [8,9,47]. Due to variations in climate, sheep farming in South Africa is expected to have a different effect on plant species and biodiversity [21,22]. In terms of land use, the European based impact assessments may not apply in the South African context [48].

EPS is the only procedure that stipulates water usage as a specific environmental impact category [9]. 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 may not be appropriate for South Africa, and 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 6: 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 6 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 [24]. In South Africa, however, water quality indicators are more prominent in the newly introduced legislation [2] and inventory constituents that impact these indicators will most probably receive a higher priority.

5 Conclusions

The environmental criteria considered by the five LCIA procedures are summarised in **Table** 7. Although, in some cases, the chosen impact categories differ between the published methods, the classification generally follows a comprehensive list of categories that have been described [49]. 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).

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 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 [2].

Table 7: 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	✓	✓	×	✓	✓

The incorporation of this impact category is therefore important in the South African context.

Depletion of mined abiotic resources, i.e. minerals and energy, is a global impact. These environmental impacts are not region-specific and therefore the current 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 [14]. This could mean that a higher weighting value for these resources is appropriate.

The normalisation and weighting principles of the 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. 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 therefore vary significantly from the European continent [2]. This means that applying LCIA procedures that were 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. An approach is consequently needed to incorporate these resources into existing procedures.

6 Further Research Work Required

Further research is currently underway to:

Analyse the availability of South African environmental data to be used in a LCIA procedure [50], taking into account the variance in geographical regions within the country [51].

- Incorporate and modify the existing procedures with the available South African data [50], whereby human health and ecosystem quality are duly considered from a South African perspective.
- Evaluate the South African government and manufacturing industry's views of the relative importance of the air, water, land and mined abiotic resources, in order to determine weighting values for these resource groups.

With the introduction of a proposed framework for a South African LCIA procedure the wool case study introduced in this paper will be revisited to determine the significance of the procedure, compared to the existing European procedures that have been used in the South African manufacturing sector [4].

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