LCA Methodology

Characterisation and Normalisation Factors for Life Cycle Impact Assessment Mined Abiotic Resources Categories in South Africa

The manufacturing of catalytic converter exhaust systems as a case study

Kerwin Strauss[1], Alan C Brent[2] and Sibbele Hietkamp[1]*

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

* **Corresponding author** (shietkam@csir.co.za)

DOI: http://dx.doi.org/10.1065/lca2004.10.183

Abstract

Goal and Background. Current Life Cycle Impact Assessment (LCIA) procedures have demonstrated certain limitations in the South African manufacturing industry. The aim of this paper is to propose new characterisation and normalisation factors for classified mined abiotic resource depletion categories in the South African context. These factors should reflect the importance of mined resources as they relate to region-specific resource depletion. The method can also be applied to determine global factors.

Methods. The reserve base (as in 2001) of the most commonly produced minerals in South Africa is used as basis to determine characterisation factors for a non-renewable mineral resources category. The average production of these minerals from 1991 to 2000 is compared to economically Demonstrated and Demonstrated Marginal Reserves (and not ultimate reserves) to obtain the characterisation factors in equivalence units, with platinum as the reference mineral. Similarly, for a non-renewable energy resources category, coal is used in South Africa as equivalent unit as it is the most important fossil fuel for the country. Crude oil and natural gas resources are currently obtained from reserves elsewhere in the world and characterisation factors are therefore determined using global resources and production levels. The normalisation factors are based on the total economic reserves of key South African minerals and world non-renewable energy resources respectively. A case study of the manufacturing of an exhaust system for a standard sedan is used to compare LCIA results for mined abiotic resource categories that are based on current LCIA factors and the new South African factors.

Results and Discussion. The South African LCIA procedure differs from current methods in that it shows the importance of other mined resources, i.e. iron ore and crude oil, relative to PGMs and coal for the manufacturing life cycle of the exhaust system. With respect to PGMs, the current characterisation factors are based on the concentrations of the metals in the ores and the ultimate reserves, which are erroneous with respect to the actual availability of the mineral resources and the depletion burden placed on these minerals is consequently too high.

Conclusions. The South African LCIA procedure for mined abiotic resources depletion shows the significance of choosing a method, which is inline with the current situation in the mining industry and its limitations.

Recommendations and Outlook. It is proposed to similarly investigate the impacts of the use of other natural resource groups. Water, specifically, must receive attention in the characterisation phase of LCIAs in South African LCAs.

Keywords: Catalytic converter exhaust systems, manufacturing; environmental performance; life cycle impact assessment (LCIA); mined abiotic resources categories; resource depletion; South Africa

1 Introduction

A framework for Life Cycle Impact Assessments (LCIAs) has been proposed for Life Cycle Assessment (LCA) studies in South Africa [1,2]. The framework shows that impacts should be calculated separately on four natural resource groups as Areas of Protection (AoP): air, water, land and mined abiotic resources. In terms of the latter, the framework addresses the impacts on mineral and energy reserves separately. However, the characterisation models that are used for the classified mineral and energy categories (and other categories) have been questioned in the South African (and World) context [1, 3]. Furthermore, the normalisation procedure that has been proposed through the framework focuses on the current and target state of mined abiotic resources [1,2]. Where new characterisation procedures are introduced for mineral and energy resource categories, the normalisation factors should be revised.

1.1 Characterisation models for the use of natural abiotic resources

Literature distinguishes between three types of natural abiotic resources: deposits, funds and flows [4]. This paper focuses on deposits, i.e. mineral (metallic and non-metallic) and energy reserves, or mined abiotic resources, that are depleted by industrial activities and which are not regenerated within human lifetimes. The United Nations Environmental Programme (UNEP) and the Society for Environmental Toxicology and Chemistry (SETAC) global life cycle initiative [5], and especially the deliverables of the LCIA Programme of the initiative, addresses the use of these resources. The background documentation of the definition study of the LCIA Programme [6] indicates that the impacts associated with mined abiotic resource use depends on the future availability of the specific resource and the technologies that will be available to provide the resource in the required quality.

The existing impact assessment methods for the mined abiotic resource categories have been defined to fall into six groups [4]:

- No aggregation or assessment of mined abiotic resource depletion in the characterisation phase of LCIAs (but rather in later phases, e.g. during weighting) [7].
- Aggregation of natural resource extractions on a mass basis [8].
- Aggregation and assessment based either on the quantity of resource that is ultimately available, or the (perceived) part of the reserve base that can be economically extracted, and the extraction rate at the time of the assessment [9–12].

- Aggregation and assessment based on the cost associated with substituting current extraction processes by improved (presumed) sustainable processes [13].
- Aggregation and assessment based on energy or exergy content or change [7,14].
- Aggregation and assessment based on the change in the anticipated environmental impact of the resource extraction process due to lower-grade deposits that have to be mined in the future [15,16].

In terms of energy consumption as a means of assessment and aggregation, the definition study of the LCIA Programme [6] indicates that future energy requirements for technologies for the depletion of mined abiotic resources have been suggested [17] with additional operational contributions [15,16,18,19]. One of these operational procedures that are commonly used for decision support in the manufacturing sector of South Africa, the Eco-indicator 99 method [16], only takes into account the long-term trends of lowering resource quality. The method assumes that if the quality of a mined abiotic resource is reduced over time, the effort to extract the remaining resource will increase. Market forces will further ensure that the highest quality of the resource is exploited at all times. The increased future efforts are expressed in surplus energy units, i.e. the difference between the energy that is needed to extract a resource presently and at some point in the future. The future surplus energy calculation is based on an arbitrary multiplication of the amount of a resource that has been extracted prior to 1990 [15]. The most important strong point of the method is that the modelling is not directly dependent on estimates of future reserves and annual consumption, which are difficult to predict. The main weak points are specified as the following [16]:

- The assumption that there will be no sudden and discontinuous changes in the gradual decrease of resource quality. In the case of oil and natural gas resource certain abrupt changes are to be expected.
- All mineral resources are considered to be of equal importance to mankind over time.
- The possibilities of substitution of a mineral by another are not taken into account.

Another characterisation procedure that is commonly used in South Africa, the CML methodology [4], applies the ultimate reserves and rates of extraction approach, which reflect the seriousness of resource depletion [10]. The characterisation factor is referred to as the Abiotic Depletion Potential (ADP) of each resource compared to a reference resource through the following formula (for mineral resources) [4]:

$$ADP_i = \frac{DR_i}{(R_i)^2} \times \frac{(R_{ref})^2}{DR_{ref}} \quad (1)$$

Where

ADP_i= Abiotic Depletion Potential of resource i (dimensionless)
R_i= Ultimate reserve of resource i (kg)
DR_i= Extraction rate of resource i ($kg.yr^{-1}$)
R_{ref} = Ultimate reserve of the reference resource, *viz.* antimony (kg)
DR_{ref} = Extraction rate of the reference resource ($kg.yr^{-1}$)

This method is partly operational as ADPs have been developed for elements only [9], and not for resources as are recorded in Life Cycle Inventories (LCIs). With respect to the use of energy resources a DR_i (in $MJ.yr^{-1}$) and R_i (in MJ) has been determined for fossil energies in general and an ADP factor subsequently calculated per MJ used. ADPs for the separate energy resources are thereafter determined based on the specific heating values of the resources. The main weak point of this approach is that it is based on the estimation of the quantities of remaining stocks, which is difficult without defining the quality requirements for the resource (in the future). Furthermore, the method does not take into account different extraction scenarios or technologies that will be available in the future.

The background documentation of the LCIA working group of the global life cycle initiative describes the importance of dissipative use as the state of the art approach to characterise mined abiotic resources, although no definite methodology is introduced [6]. The current situation with practically all metals is that a certain amount in usage is annually recycled and virgin metal is added to the amount that is currently in use. Mineral consumption rose significantly in the twentieth century and particularly since 1960 [20]. Overall only a small fraction of the metals is removed from the global inventory by dissipative use. This is the case for a relatively inexpensive metal such as iron and much more so for an expensive metal such as platinum. Therefore, the attention should not only be on the dissipative use at present, but also on the increase of most metals that is in use. This increasing amount of metals in use leads to the ongoing depletion of the natural reserves, i.e. through the mining industry.

1.2 Normalisation factors for mineral and energy resources

Normalisation factors are also stipulated separately for the available operational procedures. In the case of the Eco-indicator 99 method [16], the total inventory of mass and energy used (mostly for 1993 as base year) for the whole of Western Europe (assumed population of 495 million) for one year per person is used as the basis for the normalisation factors. Where country-specific information was inadequate the ratios of total energy usage and Gross Domestic Product (GDP) were used to estimate the yearly usage of the separate resources.

The operational documentation of the CML method recommends the use of normalisation data based on one geographically and temporally well-defined reference system, preferably the world for one year [4]. Thereby, the normalisation factors are based on the ultimate reserves in the world combined with yearly depletion on a world level. These reserve and extraction values are based on various literature sources.

The main sources of errors with determining normalisation factors are attributable to the reliability of data and the uncertainty (in the application of) characterisation factors [21]. Of specific concern is the aggregation and consequent disregard of region-specific impacts, i.e. mined abiotic resources may be at a high level of depletion in certain regions, which would be regarded as a high concern compared, for example, to the world reserves. The contributions of a life cycle system to separate abiotic resource-related problems are therefore not clearly visible in the normalisation results of a LCIA study [22].

1.3 Objectives of this study

This paper introduces a modified approach to the characterisation and normalisation phases of LCIAs for classified mined abiotic resource categories. The characterisation factors, together with normalisation values, better reflect the impacts associate with the usage of a life cycle system of mined abiotic resources in a regional context, *viz.* South Africa. The subcategories that are introduced, namely mineral and energy reserves, specifically address the mined abiotic resource usage of the process industry in South Africa. The manufacturing of a catalytic converter and assembly in an exhaust system of a typical sedan is used as a screening LCA (SLCA) case study, to compare the modified procedure with two operational procedures that are currently used in the South African manufacturing industry, i.e. Eco-indicator 99 and CML.

2 Modified Approach to Characterisation and Normalisation of Mined Abiotic Resources in South Africa

2.1 South African characterisation factors for mined abiotic resources

In 2001 the South African national Department of Minerals and Energy (DME) determined a 'reserve base' for the most common minerals that are currently produced and consequently of importance to the process industry in South Africa [23]. The most important fossil fuel energy resource for the economy, *viz.* coal, was also included in the study. The reserve base is defined by DME as that part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices, including those for grade, quality, thickness, and depth. These parameters encompass those parts of the resource that have a reasonable potential for becoming economically available within planning horizons beyond those that assure proven technology and current economics. The reserve base is subdivided into those resources that are currently economic (Demonstrated Reserves) and those that are marginally economic (Demonstrated Marginal Reserves). Demonstrated Marginal Reserves refer to that part which, at the time of determination, borders on being economically producible [24]. Its essential characteristic is economic uncertainty and included are resources that would be producible, given postulated changes in economic or technologic factors. In terms of the proposed approach in this article only Demonstrated Reserves are included in the resource base.

For each of the resources, the average production from 1991 to 2000 is calculated and compared to the Demonstrated Reserves for 2001. The ten-year average is used to minimise the effect of annual fluctuations. The model therefore has to be updated at least every ten years. Reserves are updated regularly and internationally published [20]. Historically short-term changes are normally not dramatic and therefore it is expected that such changes will not strongly influence the outcome of a LCA study. For example, in the case of South African platinum resources, the Demonstrated Reserve was increased by 25% in 1996, but remained constant thereafter [20]. Although it would be preferred to have definitive numbers, the drawback is that such numbers, if poorly known, would add to the uncertainty in the outcome of a LCA study. Furthermore, it is not uncommon that changes in characterisation factors (of all impact categories) should be considered when examining the results of previously conducted LCAs. For example, Global Warming Potential equivalency factors are regularly reviewed [25].

The result of the average production calculation and comparison with the Demonstrated Reserve is an impact score that is directly related to the depletion of resources. The ratio of the average annual production to the economic reserve (*depletion factor*) determines the rate of depletion:

$$D_f = \frac{P}{R} \tag{2}$$

Where
D_f = Depletion factor
P = Average annual production of virgin material ($kg.yr^{-1}$)
R = Economic reserve for the mineral (kg)

A smaller ratio indicates a slower rate of depletion. This penalises minerals with a high production to reserve ratio, i.e. minerals that are currently being depleted at a faster rate.

In addition to this, the actual use of the mineral for a specific process should be weighed against what is currently available to determine its relative impact, i.e. by comparing the actual use of the mineral to its economic reserve (*Use factor*):

$$U_f = \frac{m}{R} \tag{3}$$

Where
U_f = The Use factor that relates the mass of virgin material used in a specific process to what is economically mineable
m = Amount of virgin material used in a specific process (kg)

The calculated impact score of a mineral χ (in a specific process) is the product of the *Depletion factor* and *Use factor*:

$$I_x = \left(\frac{P_\chi}{R_\chi^2}\right) \times m_\chi = \left(\frac{P_\chi}{R_\chi^2}\right) \text{ (per kg } \chi) \tag{4}$$

For aggregation purposes, the impact scores must have a common unit. This is achieved through the use of equivalents, with platinum as the reference mineral. The impact of the use of one mineral can be stated in platinum equivalents by comparing its potential impact to the equivalent in platinum. Platinum is used as the reference mineral in recognition of the large role it has played, and is currently playing, in the South African economy, and its extensive functional properties in society. The potential impact can be described as a factor that converts the mass used to its characterisation value. The characterisation factor for a mineral χ (C_χ) is subsequently calculated by finding the ratio between the impact score for mineral χ to that of platinum:

$$C_\chi = \frac{P_\chi}{R_\chi^2} \times \frac{R_{platinum}^2}{P_{platinum}} \text{ (kg platinum equivalents per kg } \chi) \tag{5}$$

Table 1: Characterisation factors for the depletion of certain South African mineral resources

Mineral	10 yr average annual production (tonnes/year)	Reserve (2001) (tonnes)	Impact score (per kg χ)	Characterisation factor (kg platinum eq.)	Reserve (kg platinum eq.)
Antimony	4.41×10^{3}	2.50×10^{5}	7.05×10^{-8}	9.39×10^{-1}	2.35×10^{5}
Cobalt	2.62×10^{2}	1.50×10^{4}	1.16×10^{-6}	1.55×10^{-1}	2.32×10^{3}
Copper	1.61×10^{5}	1.30×10^{7}	9.51×10^{-10}	1.27×10^{-2}	1.65×10^{5}
Fluorspar	2.19×10^{5}	8.00×10^{7}	3.42×10^{-11}	4.56×10^{-4}	3.65×10^{4}
Gold	5.27×10^{2}	3.60×10^{4}	4.07×10^{-7}	5.42×10^{0}	1.95×10^{5}
Iron Ore	3.02×10^{7}	1.50×10^{9}	1.34×10^{-11}	1.79×10^{-4}	2.68×10^{5}
Lead	8.48×10^{4}	3.00×10^{6}	9.42×10^{-9}	1.26×10^{-1}	3.77×10^{5}
Manganese Ore	3.03×10^{6}	4.00×10^{9}	1.90×10^{-13}	2.53×10^{-6}	1.01×10^{4}
Nickel	3.23×10^{4}	1.20×10^{7}	2.24×10^{-10}	2.98×10^{-3}	3.58×10^{4}
Platinum	1.16×10^{2}	3.93×10^{4}	7.51×10^{-8}	1.00×10^{0}	3.93×10^{4}
Palladium	5.83×10^{1}	1.98×10^{8}	1.49×10^{-7}	1.98×10^{0}	3.93×10^{4}
PGMs	1.85×10^{2}	6.28×10^{4}	4.68×10^{-8}	6.24×10^{-1}	3.93×10^{4}
Rhodium	1.11×10^{1}	3.77×10^{3}	7.82×10^{-7}	1.04×10^{1}	3.93×10^{4}
Silver	1.70×10^{2}	1.00×10^{4}	1.70×10^{-6}	2.27×10^{1}	2.27×10^{5}
Uranium	1.60×10^{3}	2.84×10^{5}	1.98×10^{-8}	2.64×10^{-1}	7.49×10^{4}
Zinc	7.11×10^{4}	1.50×10^{7}	3.16×10^{-10}	4.21×10^{-3}	6.32×10^{4}

Table 2: Characterisation factors for the depletion of energy resources

Fossil fuel	10 yr average annual production (tonnes/year)	Reserve (2001) (tonnes)	Impact score (per kg χ)	Characterisation factor (kg coal eq.)	Reserve (kg coal eq.)
Coal (World)	4.54×10^{9}	9.84×10^{11}	4.69×10^{-15}	1.00×10^{0}	9.84×10^{11}
Crude Oil (World)	3.34×10^{9}	1.43×10^{11}	1.64×10^{-13}	3.50×10^{1}	5.01×10^{12}
Natural Gas (World)	1.97×10^{9}	1.40×10^{11}	1.01×10^{-13}	2.15×10^{1}	3.01×10^{12}

The resulting characterisation factor takes the same form as that used in the CML method, but using economic (proven) reserves in place of ultimate reserves. **Table 1** summarises the characterisation factors for a number of minerals in the South African context.

As stated before, the South African economy relies heavily on coal as an energy resource. Although natural gas fields have recently been discovered off the coast of Southern Africa [26], crude oil and natural gas that are used for economic activities are currently largely obtained from reserves elsewhere in the world. Therefore, in terms of calculating characterisation factors for all non-renewable energy resources, the average annual production and economic reserves of the world are used [27] (**Table 2**).

2.2 South African normalisation values for mined abiotic resources

The South African normalisation factors follow the same principle used by the CML method. However, the characterisation factors are based on economic reserves and not on ultimate reserves. The characterisation factor is divided by the sum of the economic reserves expressed in platinum equivalents (or coal equivalents) for normalisation. The normalisation factor is therefore:

$$N = \frac{1}{\sum_{2001} R} \quad \text{(kg equivalents)} \qquad (6)$$

In South Africa the total economic mineral reserves are equal to 1.81×10^{6} kg platinum equivalents (see Table 1), and the normalisation factor for the classified mineral depletion category is therefore 5.52×10^{-7}. In terms of fossil fuels, the total world reserves (including world oil and natural gas) is equal to $6.19\text{x}10^{11}$ kg coal equivalents (see Table 2), and the normalisation factor for the classified energy depletion category is therefore $1.62\text{x}10^{-12}$.

3 Case Study: The manufacturing of catalytic converter exhaust systems in South Africa

The South African automotive industry generates approximately 1.2 billion Euros annually in foreign revenue from the export of automotive components. The main destination of the components is the European Union, and the most important component is exhaust systems with catalytic converters (**Fig. 1**) [28]. The latter can be attributed to the large South African platinum industry. South Africa is estimated to have 88% of the world's economically recoverable reserves of platinum [29]. Of increasing international importance, is the measurement of the environmental performance of the supply chain of purchased products, i.e. sustainable supply chain management. This requires an understanding of the region-specific environmental impacts associated with the manufacturing of the products, e.g. exhaust systems [30].

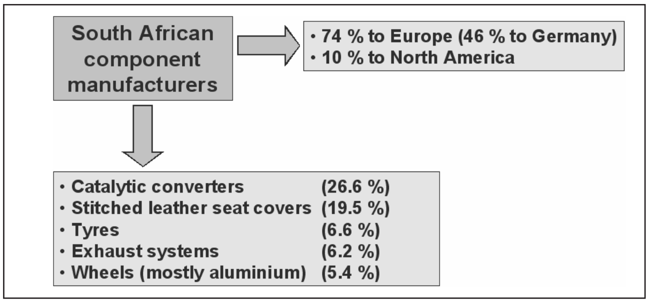

Fig. 1: The main manufactured automotive components in South Africa and export destinations (percentages reflect the economic value of all exported components)

3.1 Goal and scope of the screening life cycle assessment (SLCA) case study

3.1.1 Functional unit and boundaries of the SLCA case study

The case study considers the manufacturing of an exhaust system (with a catalytic converter) in South Africa for use in a specific sedan with the intent to export, i.e. it is a cradle-to-gate SLCA of an exhaust system supplied to an automobile Original Equipment Manufacturer (OEM). The actual use and disposal of the exhaust system (and catalytic converter) is not included, as these stages of the life cycle are uniform irrespective of the manner by which the exhaust systems are manufactured. The subcomponents of such a sedan-specific exhaust system, as supplied to an OEM for assembly into the sedan, are summarised in **Table 3**. The total mass of one exhaust system, ready for assembly in a sedan, i.e. the functional unit of the study, is approximately 34 kg and the total economic value in the order of 3000 Euros. 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 [31]. 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 [32]. The functional unit of this case study does not have an actual energy value and this parameter is not included in the RMEE method. It should be noted that problems have been associated with cut-off procedures in life cycle studies [33]. However, for this 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.

3.1.2 Allocation of environmental impacts of the SLCA case study

The base metal extraction process to obtain the platinum group of metals (PGMs) for the catalytic converter of the exhaust system highlights the production of minerals other than PGMs. Allocation is therefore necessary to determine the impacts for the production of the separate minerals. The mass of produced PGMs is typically a factor of approximately 1000 less than the produced base metals [34]. Where gate-to-gate LCAs have been conducted in this industry sector, it has subsequently been proposed to base the allocation on the mass of produced metals [35]. However, with respect to the use of the produced metals in further life cycle systems, the PGMs contribute approximately 85% of the total revenue from the ore body [34]. Therefore, in South Africa, the mines are true PGM mines and the value of the base metals would not have justified the mining operation. For the SLCA case study the allocation is subsequently based on the *economic value* of the metals extracted.

Table 3: Subcomponents of a sedan-specific exhaust system manufactured in the Republic of South Africa (RSA)

Subcomponent	Function	Material	Weight	Supplier
Exhaust casing	Houses the catalytic converter	411 SS	23.2 kg	Columbus Steel (RSA)
Mantel	Outer housing	411 SS	0.8 kg	Columbus Steel (RSA)
Coated ceramic bricks (monolith)				
Ceramic bricks	Catalyst support	talc, koalin, alunmina, cordierite	1.4 kg (for 2 bricks)	NGK (Japan, RSA)
PGM catalyst	Reduction of harmful gases	platinum, rhodium, palladium	6.5 g	Western Platinum (RSA)
Washcoat	Carrier for PGMs	Al_2O_3 (10%), CeO_2 (20%), ZrO_2 (70%)	0.2 kg	Horias (RSA)
Cones	Fits converter to exhaust piping	309 SS	0.7 kg	GBG (RSA)
Expanding mats	Cones wrapping for insulation	Durablanket textile	< 0.1 kg	Feltex (USA)
Insulation mats	Cones fittings for insulation	Durablanket textile	< 0.1 kg	Carborandum Company (RSA)
Heat shields	Inner spacers	1.4301 SS	0.3 kg	ZS Augsburg (Germany)
Plastic spacer rings	Outer spacers	No information	< 0.1 kg	GP Plastics (RSA)
Wire mesh rings	Holds ceramic bricks together	310 SS	0.5 kg	Catalyst Support Systems (RSA)

3.1.3 The purpose of the SLCA case study

The compiled life cycle system utilises a variety of non-renewable mineral and energy resources. The exhaust system SLCA is therefore a good case study to compare the results of the Life Cycle Impact Assessment (LCIA) phase of the SLCA, using the Eco-indicator 99, CML, and modified South African approach for non-renewable resource use categories only. Thereby, only the input streams of non-renewable resources to the unit process (included in the boundaries) are considered in the SLCA case study.

3.2 Life Cycle Inventory (LCI) analysis of the screening life cycle assessment (SLCA) case study

A simplified process diagram for the manufacturing of an exhaust system is shown in **Fig. 2**. The following sources were used to obtain the non-renewable resource inputs to the unit processes:

- Personal interviews, held with the South African process and manufacturing industries.
- Company-specific publications, e.g. environmental reports.
- International literature and reference material.

The most important input constituents in terms of non-renewable resources (in South Africa) are summarised in **Table 4**. These life cycle inventory (LCI) constituents contribute more than 99% to the non-renewable impact categories of the Eco-indicator 99, CML, and modified South African approach of the LCIA. Therefore, although all of the unit processes (shown in Fig. 2) do use noteworthy amounts of non-renewable resources separately, the three LCIA methods do not highlight the excluded unit processes (and other input non-renewable streams) as significant when considering the overall life cycle system (of the functional unit).

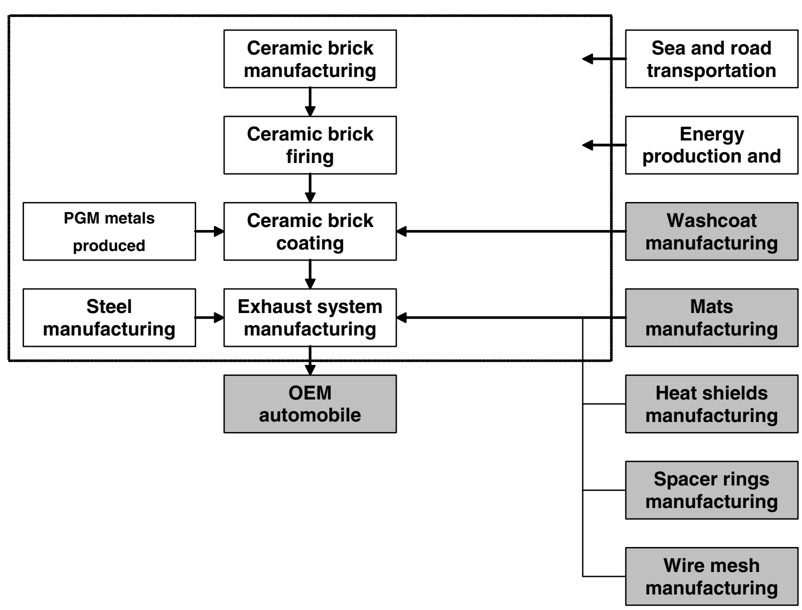

Fig. 2: The life cycle of the manufacturing of an exhaust system in South Africa. **Shaded areas:** processes not included in the boundaries of the life cycle system. **Non-shaded areas:** processes included in the boundaries of the life cycle system

Table 4: Life Cycle Inventory (LCI) profile of the exhaust life cycle system

	Non-renewable input stream	Value	Unit processes (in Fig. 2)
Mineral resources	Iron (from ore)	31.6 kg	Steel manufacturing, Catalytic converter manufacturing
	PGM, primarily platinum (from ore)	6.5g	PGM metals manufacturing, Ceramic brick coating
Energy resources	Coal	710 kg	Electricity generation, All other unit processes
	Crude oil	427 kg	Energy production and generation, Sea and road transportation
	Natural gas	50.3 kg	Energy production and generation, Road transportation

3.3 Life Cycle Impact Assessment (LCIA) of the screening life cycle assessment (SLCA) case study

3.3.1 Characterisation

The characterisation results for the mineral and energy resources categories (for the three LCIA methodologies evaluated and compared in this paper) are shown in **Fig. 3** and **Fig. 4**. Per manufactured exhaust system, the Eco-indicator 99 procedure indicates the use of the platinum group of metals (PGMs) to be most important in terms of mineral resources use, and coal and crude oil in terms of energy resources use. The CML LCIA procedure indicates similar results for the mineral resources category, but with respect to energy resources shows the use of coal (for electricity generation and fuel production in South Africa) as the most important parameter. The modified South African LCIA procedure assigns the use of PGMs and iron (for steel manufacturing) as the highest characterised inventory constituents with respect to mineral resources, and the use of coal and crude oil (in the processing industry) to have the highest impact in terms of energy resources similar to the Eco-indicator 99 procedure.

3.3.1.1 Mineral resources category

The determination of the characterisation values and their impact on the outcome on the final result is of great importance, and warrants further discussion. The focus of the discussion is on the background and impact of the characterisation factors on the outcome summarised in **Table 5**.

Eco-indicator 99. Eco-indicator 99 uses a method that is based on current concentrations of ore within the earths crust and the change in these concentrations over an arbitrary period. The existing concentration of the ore within the earths crust has a larger effect on the final result than from the change in its concentration. The result is a high penalty for minerals that are mined at low concentrations. Therefore the method values the concentration of an ore much more than the scarcity. Also, the environmental impacts of concentration are dealt with under other categories such as solid waste creation, energy use, water use, etc. in the evaluation of the processing that is required to extract the required mineral from the ore. Double counting therefore occurs when placing a high weight on concentration only. The following calculations illustrate this point.

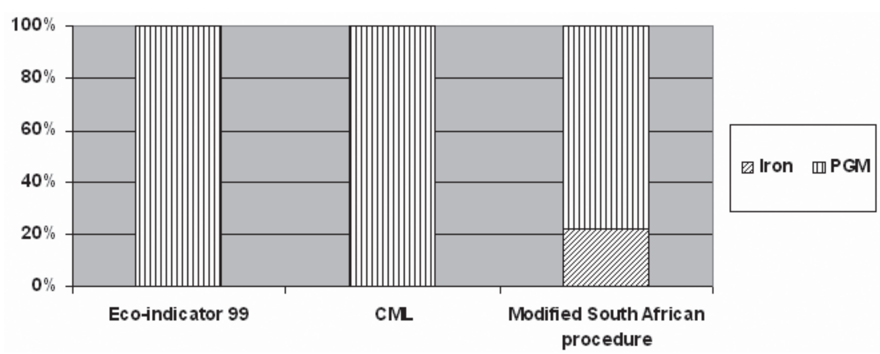

Fig. 3: Characterisation results for the mineral resources category

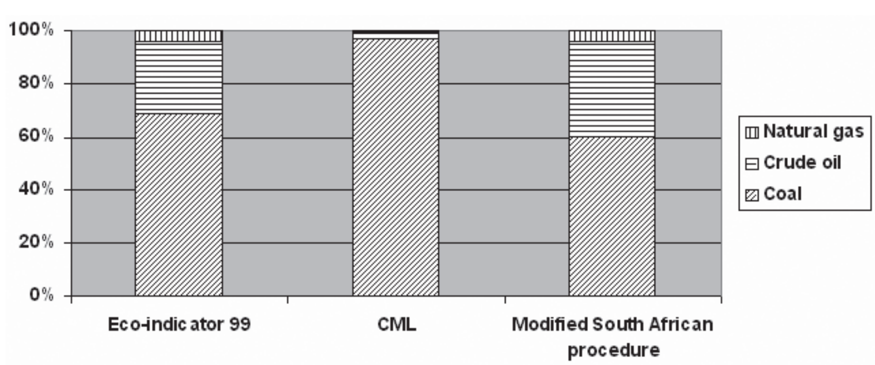

Fig. 4: Characterisation results for the energy resources category

Table 5: Summary of characterisation results for the mineral resources category from the three LCIA procedures

Mineral	Characterisation results		
	Modified SA procedure (kg platinum eq.)	CML (kg antimony eq.)	Eco-indicator 99 (MJ surplus energy)
Iron (from ore)	0.00565	0	0.916
PGMs (from ore)	0.01945	0.00838	462

The Eco-indicator 99 expresses the impacts on the mineral resources category in terms of surplus energy in MJ per tonne of mineral, through the following equation:

$$\frac{A}{g_2} - \frac{A}{g_1} \qquad (7)$$

Where

A = The energy used for mining (400MJ/t for open pit, 1000MJ/t for underground, constant for all ores)
g_1 = The ore grade of presently mined ores
g_2 = The ore grade of future mined ore grades (when 5 times the current amount has been extracted)

The parameter g_2 is calculated from g_1 using the cumulative probability distribution (g, Q) of ore grades:

$$\log g_2 = \log g_1 - \frac{0.6989}{m} \qquad (8)$$

Where log is the base 10 logarithm and m is estimated from readings of (g, Q) distributions; for platinum, m = 5.6 [36]. Using a current ore grade of 4.7×10^{-4}% for g_1, the surplus energy (for platinum) for underground mining is derived as 7.083×10^{7} MJ/t.

The above calculation shows that the characterisation factor has a high dependency on the current concentration of the mineral in the ore body and not on the change in its concentration. This is further demonstrated by substituting platinum with iron in the equations. Using the same m value, i.e. same change in concentration over time, and, for consistency, assuming underground mining, together with an iron concentration in typical ore of 70%, the surplus energy for iron is calculated to be 4.76×10^{2} MJ/t. If an opencast situation is assumed for iron ore, i.e. a value of 400 MJ/t for the parameter A in equation 7, the surplus energy for platinum is calculated to be 2.83×10^{7} MJ/t and for iron 1.91×10^{2} MJ/t.

A difference in the characterisation factor of 5 orders of magnitude for similar and different conditions and different concentrations shows the dependency on current concentrations, which are not synonymous with scarcity.

CML. The CML method uses annual production figures and ultimate reserves to determine characterisation factors (see equation 1 in section 1.1). **Table 6** summarises the characterisation factors for platinum and iron in comparison to the reference mineral of CML, i.e. antimony. The estimated reserves are averaged over the earths crust to depths beyond current mining practices.

There exists a high uncertainty upon which these estimates are based in terms of actual quantities and future available technology. The effects of using ultimate reserves are more clearly visible in the normalisation step and will be given more attention there.

Modified South African procedure. The results show that the use of 31.6 kg of iron (from ore) is comparable to the use of 6.5 g of platinum, i.e. a factor of approximately 3 orders of magnitude, which is a dissimilar result to the other two methods. By using 6.5 g of PGMs, the life cycle system reduces the economic reserve (6.28×10^{4} tonnes) by this amount, or by 1.04×10^{-8}%. By using 31.6 kg of iron, the economic reserve (1.50×10^{9} tonnes) is therefore reduced by this amount, which is 2.11×10^{-9}%. The actual depletion of economic reserves differs by a factor of 1 order of magnitude, which is comparable with the characterisation results.

3.3.1.2 Energy resources category

The characterisation results are summarised in **Table 7**. The results show the use of coal is the dominant fossil fuel for all models, and specifically for the energy requirements in PGM mining, processing and auxiliary unit processes.

Eco-indicator 99. The Eco-indicator 99 procedure assumes the full substitution of energy sources and has produced various scenarios for substitution, including oil replaced by shale oil and lignite being substituted by brown coal. In the case of oil the extra energy required to remove shale oil as compared to conventional oil is much greater than the difference between lignite and brown coal. This results in a higher penalty for oil than for coal.

CML. Similar to the Eco-indicator 99 model, the CML procedure also assumes the full substitution of energy sources. All fossil fuels are summed based on their ultimate reserves in energy units. The ultimate reserves are estimated from economic databases. The ratio of carbon in geological formations to proven carbon reserves is used to convert economic reserves to ultimate reserves. The fossil fuels are then characterised by this common reserve multiplied by the heating value of the specific fossil fuel.

Table 6: CML characterisation factors with antimony as the reference mineral

Mineral	Extraction (kg/yr)	Ultimate reserve (kg)	Characterisation factor
Antimony	6.06×10^{7}	4.63×10^{15}	1
Platinum	4.90×10^{4}	1.16×10^{14}	1.29
Iron	4.05×10^{11}	1.30×10^{21}	8.43×10^{-8}

Table 7: Summary of characterisation results for the mineral resources category from the three LCIA procedures

Mineral	Characterisation results		
	Modified SA procedure (kg coal eq.)	CML (kg antimony eq.)	Eco-indicator 99 (MJ surplus energy)
Coal	790	10.6	199
Crude Oil	472	0.271	79.9
Natural Gas	53	0.0512	11.9

Modified South African procedure. The characterisation factors are based on the comparison of each fossil fuel with its reserve. As there is a large difference in global reserves between coal and oil, i.e. coal is much more abundant, the characterisation factor for oil gets a larger rating then the one for coal.

3.3.2 Normalisation

Eco-indicator 99. The normalisation step of the Eco-indicator 99 procedure (**Fig. 5**) places the same emphasis on the use of energy resources as that on mineral resources, and shows that the use of PGMs is the most important environmental parameter in terms of overall resource use in the manufacturing life cycle of the exhaust system. The effect of the low concentration at which platinum is mined therefore filters through to the normalisation step and finally to the Single Score. This has a large impact on the outcome of the LCA.

CML. The CML procedure uses the same normalisation factor for both categories, i.e. it considers abiotic depletion as a single category. The results show that the use of the required fossil fuel resources completely overrides the importance of the mineral resources (**Fig. 6**). Specifically, the use of coal in the life cycle is indicated to be the most important environmental consideration. By taking into consideration all the resources present in the earth's crust, including resources that are unlikely ever to be classified as reserves, the scarcity of the minerals is underestimated

Modified South African procedure. The modified South African LCIA procedure highlights the use of PGMs, iron, coal and crude oil resources to be the main consideration with respect to the overall mineral and energy resource use in the exhaust system life cycle (**Fig. 7**). This correlates well with the amounts used in conjunction with their economic scarcity. The results are therefore a reflection of the current situation, in terms of availability of minerals, and the effect of their uses in industry.

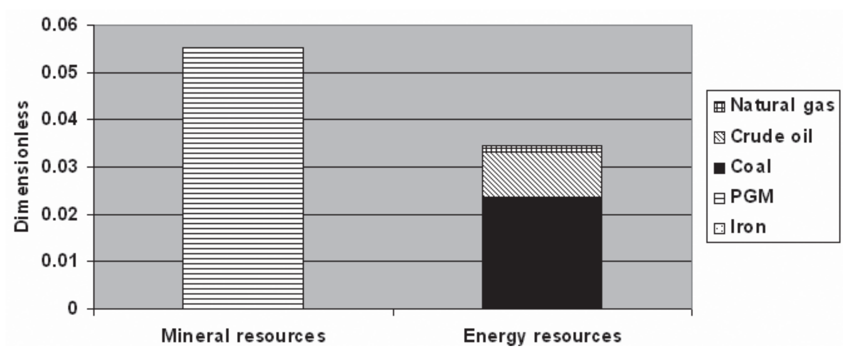

Fig. 5: Normalisation results of the Eco-indicator 99 procedure for the exhaust system life cycle

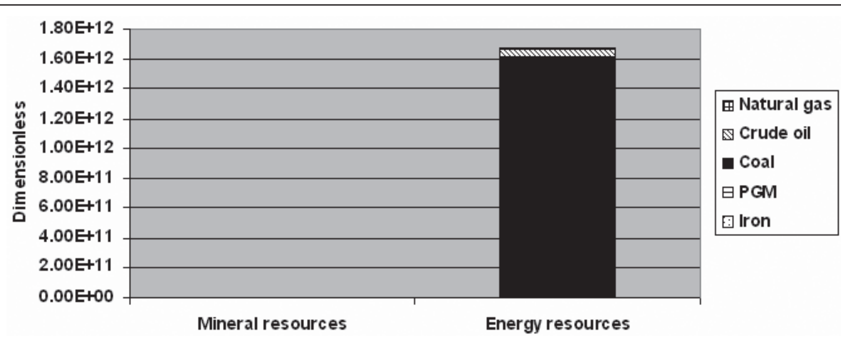

Fig. 6: Normalisation results of the CML procedure for the exhaust system life cycle

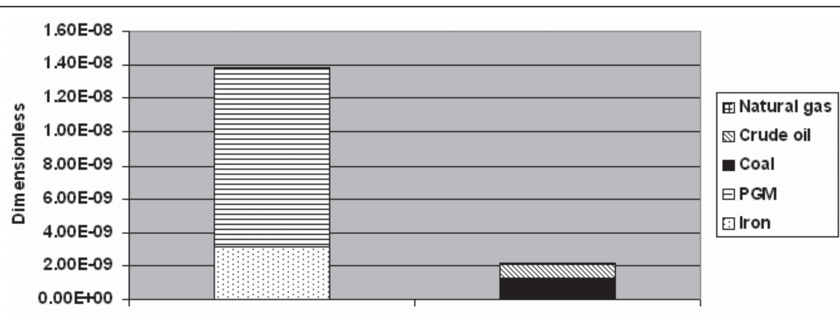

Fig. 7: Normalisation results of the modified South African LCIA procedure for the exhaust system life cycle

4 Conclusions

The characterisation approach and normalisation values of the modified South African LCIA procedure for abiotic resource depletion show the significance of choosing a method, which is inline with the situation in the mining industry and its limitations. The availability of resources for economic activities differ between regions, and the importance of the resources is consequently perceived to be different within regions compared to a global scale. The method can therefore be applied on both a regional and global scale depending on the specific requirements of the LCA practitioner.

The modified South African LCIA procedure proposes that the economical reserves should be used to obtain equivalency characterisation factors for mined abiotic resources categories in place of ultimate reserves. The same applies for the normalisation step.

Similar to the mined abiotic resources categories, the use of other natural resources in South Africa (as environmental impact categories) will be investigated. Specifically the use of water as a resource should be differentiated with respect to surface and groundwater reserves, as has been documented in the definition study of the global life cycle initiative's LCIA programme.

References

[1] Brent AC (2003): A proposed lifecycle impact assessment framework for South Africa from available environmental data. SA J of Science 99 (3/4) 115–122

[2] Brent AC (2004): A Life Cycle Impact Assessment procedure with resource groups as Areas of Protection. Int J LCA 9 (3) 172-179

[3] Brent AC, Hietkamp S (2003): Comparative evaluation of Life Cycle Impact Assessment methods with a South African case study. Int J LCA 8 (1) 27–38

[4] Guinée JB, Gorrée M, Heijungs R, Huppes G, Kleijn R, de Koning A, van Oers L, Sleeswijk AW, Suh S, Udo de Haes HA, de Bruijn H, van Duin R, Huijbregts MAJ (2001): Life cycle assessment – an operational guide to the ISO standards – Part 3: Scientific background. Centre for Environmental Studies (CML), Leiden University, Leiden, the Netherlands

[5] United Nations Environmental Programme (2002): The global life cycle partnership <http://www.uneptie.org/pc/sustain/lca/lca.htm>, accessed on 25 June 2003

[6] Jolliet O, Brent AC, Goedkoop M, Itsubo N, Müller-Wenk R, Peña C, Schenk R, Stewart M, Weidema BP (2003): Life Cycle Impact Assessment definition study: Background document III. Final draft report, LCIA Programme, UNEP/SETAC Life Cycle Initiative <http://www.uneptie.org/pc/sustain/lcinitiative/lcia_program.htm>, accessed on 25 June 2003

[7] Udo de Haes HA (ed) (1996): Towards a methodology for Life Cycle Impact Assessment. SETAC-Europe, Brussels, Belgium

[8] Lindfors L-G, Christiansen K, Hoffman L, Virtanen Y, Juntilla V, Hanssen O-J, Rønning A, Ekvall T, Finnveden G (1995): Nordic Guidelines on Life-Cycle Assessment. Nord 1995:20, Nordic Council of Ministers, Copenhagen, Denmark

[9] Guinée JB (1995): Development of a methodology for the environmental life-cycle assessment of products; with a case study on margarines. Thesis, Leiden University, Leiden, the Netherlands

[10] Guinée JB, Heijungs R (1995): A proposal for the definition of resource equivalency factors for use in product Life-Cycle Assessments. Environ Toxicol Chem 14 (5) 917–925

[11] Goedkoop M (1995): The Eco-indicator 95. NOH Report 9523, Pré Consultants B.V., Amersfoort, the Netherlands

[12] Hauschild M, Wenzel H (1998): Environmental assessment of products. Volume 2: Scientific background. Chapman & Hall, London, United Kingdom

[13] Steen B (1995): Valuation of environmental impacts from depletion of metal and fossil mineral reserves and from emission of CO_2. AFR Report, Swedish Waste Research Council, Stockholm, Sweden

[14] Finnveden G (1996): Life cycle assessment as an environmental systems analysis tool – with a focus on system boundaries. Licentiate thesis, AFR Report 137, Swedish Waste Research Council, Stockholm, Sweden

[15] Müller-Wenk R (1998): Depletion of abiotic resources weighted on base of 'virtual' impacts of lower grade deposits used in the future. IWÖ Diskussionsbeitrag nr. 57, University of St. Gallen, Switzerland

[16] Goedkoop M, Spriensma R (2000). The eco-indicator 99 – A damage oriented method for life cycle impact assessment. Methodology report, Pré Consultants B.V., Amersfoort, the Netherlands

[17] Steen B, Ryding S-O (1992): The EPS-Enviro-Accouniting method: An application of environmental accounting principles for evaluation and valuation of environmental impact in product design. AFR-Report 11, Swedish Waste Research Council, Stockholm, Sweden

[18] Weidema BP (2000): Can resource depletion be omitted from environmental impact assessments? Poster presented at SETAC World Congress, Brighton, United Kingdom

[19] Steen B (1999): A systematic approach to environmental priority strategies in product development (EPS) – version 2000 – general system characteristics. Centre for Environmental Assessment of Products and Material Systems (CPM), Technical Environmental Planning, Chalmers University of Technology, Göteborg, Sweden

[20] United States Geological Survey (USGS) (2004): Minerals Yearbook: Volume I – Metals and Minerals <http://minerals.usgs.gov/minerals/pubs/commodity/myb/>, accessed on 17 May 2004

[21] Huijbregts MAJ, Breedveld L, Huppes G, de Koning A, van Oers L, Suh S (2003): Normalisation figures for environmental life-cycle assessment: The Netherlands (1997/1998), Western Europe (1995) and the world (1990 and 1995). Journal of Cleaner Production 11 (2003) 737–748

[22] Brentrup F, Küsters J, Lammel J, Kuhlmann H (2002): Impact assessment of abiotic resource consumption. Int J LCA 7 (5) 301–307

[23] South African Department of Minerals and Energy (2003): South Africa's Mineral Industry 2002/2003. Directorate: Mineral Economics, 20th revised edition, Pretoria, South Africa.

[24] United States Geological Survey (USGS), United States Bureau of Mines (1980): Principles of a resource/reserve classification for minerals. U.S. Geological Survey Circular 831 <http://imcg.wr.usgs.gov/usbmak/c831.html>, accessed on 17 May 2004

[25] United Nations Framework Convention on Climate Change (UNFCCC) (2004): Greenhouse Gas Emissions <http://unfccc.int/program/mis/ghg/index.html>, accessed on 17 May 2004

[26] Engineering News (2003): Gas to rise to 10% of SA's energy supply. Published on 30 May 2003 <http://www.engineeringnews.co.za/eng/sector/energy/?show=36130>, accessed on 15 January 2004

[27] British Petroleum (2003): BP statistical review of world energy. BP website <http://www.bp.com/centres/energy/>, accessed on 15 January 2004

[28] National Association of Automobile Components and Allied Manufacturers (NAACAM) (2003): TISA Motor Industry Development Programme (MIDP) export data for components. NAACAM website <http://www.naacam.co.za/tisa.htm>, accessed on 15 January 2004

[29] Brent AC, Rohwer MB, Friedrich E, von Blottnitz H (2002): Status of Life Cycle Assessment and Engineering research in South Africa. Int J LCA 7 (3) 167–172

[30] Brent AC (2002): Management of imported supply chain products – Incorporating country-specific sustainability criteria in life cycle decision analysis. Going Green, CARE Innovation 2002, Fourth International Symposium, International (S)CARE Electronics Office, Austrian Society for Systems Engineering and Automation, Vienna, Austria

[31] Raynolds M, Fraser R, Checkel D (2000): The relative mass-energy-economic (RMEE) method for system boundary selection. Part 1: A means to systematically and quantitatively select LCA boundaries. Int J LCA 5 (1) 37–48

[32] Raynolds M, Fraser R, Checkel D (2000): The Relative Mass-Energy-Economic (RMEE) method for system boundary selection. Part 2: Selecting the boundary cut-off parameter (ZRMEE) and its relationship to overall uncertainty. Int J LCA 2 (2) 96–104

[33] Suh S, Huppes G (2002): Missing inventory estimation tool using extended input-output analysis. Int J LCA 7 (3) 134–140

[34] Anglo American Platinum Corporation Limited (Anglo Platinum) (2003): Annual Report, <http://www.angloplatinum.com>, accessed on 17 May 2004

[35] Forbes P, von Blottnitz H, Gaylard P, Petrie JG (2000): Environmental assessment of base metal processing: A nickel refining case study. SAIMM Journal Transactions 100 (6) 347–353

[36] De Vries D (1998): Sustainable resource use, optimal depletion with a geostatistical framework. IVEM report nr. 35, Groningen, the Netherlands

Received: March 23rd, 2004
Accepted: October 10th, 2004
OnlineFirst: October 11th, 2004