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Social Life Cycle Inventory for Pavements – A Case Study of South Africa

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ABSTRACT

Social consideration, assessed using a social life cycle assessment (S-LCA), is a relatively new concept that has yet to be standardised. Attempts at measuring social sustainability in pavement management have been made in South Africa, using social impact assessments (SIAs) and empowerment impact assessment models (EmpIAs). However, these models only focus on certain social considerations and do not incorporate holistic social sustainability in evaluations. The first response to these challenges is to identify and secure universal acceptance for indicators which measure social impacts of pavements and the broader impacts of technical and managerial choices in pavement infrastructure provision. These indicators may then be used to develop a situational- and location-specific social life cycle inventory (S-LCI).

This study starts by identifying key social indicators in pavement infrastructure provision and proposes a framework for an S-LCA. Potential indicators were sourced from a large database, focusing on indicators most aligned with social sustainability. Indicators were assessed and scored using an adapted methodology and refinement was conducted through sensitivity analyses employing Bayesian-based Monte Carlo simulations. By allowing weightings and scores of sub-goals and criteria to be changed, the results reflect the importance of inputs from local stakeholders on the impacts of sustainability. A worked example is provided to demonstrate its implementation.

The framework is envisioned to function as the first version of a living protocol that will be improved on through further research. Although the primary target audience is South African road authorities, the approach can be adapted for use in any country.

Introduction

The concept of sustainable pavement infrastructure, commonly measured using life cycle cost analyses (LCCAs), or life cycle assessments (LCAs), has in the past had the connotation of assessing whether a road can be economically and environmentally operated and maintained over its design life. This concept was usually related to ensuring the road remained a cost-effective, low carbon, operational and valuable asset. In recent years, however, new concepts relating to inclusive and equitable social development and empowerment have been increasingly introduced at the design, procurement, construction, operation, and maintenance phases, with the ensuing intention to maximise social impacts.

Social consideration, assessed using a social life cycle assessment (S-LCA), is a relatively new concept that has yet to be standardised [35,69,48]. An S-LCA is similar to an (environmental) LCA in that it generally comprises four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation [69]. The evolution of S-LCAs may also be categorised into four stages, namely: the first steps towards S-LCA development (1996-2009), the years of uncertainty (2009–2012), the years of development (2013-2016), and the standardisation years (2017-present). Current attempts at S-LCA framework development focus largely on methodological standardisation where the leading efforts focus on (1) selection of key indicators and (2) assessments of subcategory [35].

In the selection of key indicators, Huarachi et al. [35] found that the most common method applied in literature was the development of a large database of possible indicators and applying social 'hotspot' technique. These 'hotspots', represented by key social indicators, describe unit processes of a product life cycle - in this study a pavement life cycle - which contribute substantially to the total social impact of the product.

One issue with database selection and development is that social impacts are often dependent on the location and, therefore, location-specific data needs to be collected for confident assessments. Furthermore, as noted by Kühnen and Hahn [48], attempts at the development of an S-LCA tend to consider a broad range of industries and sectors, with

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few receiving sufficient empirical attention to draw reasonable conclusions. An S-LCA in the field of pavement engineering is still underdeveloped and lacks empirical experience.

The first response to these challenges is to identify and secure universal acceptance for indicators [32] which measure social impacts of pavements and the broader impacts of technical and managerial choices in pavement infrastructure provision. These indicators will be used to develop a social life cycle inventory (S-LCI). A significant constraint in the development of such an inventory is the complex nature of social impacts, the relationship between indicators across the three tenets of sustainability (i.e. economic, environmental, and social), and the changing political landscape that shapes the relative weights of the indicators.

In extending the social 'hotspot' methodology, Castillo and Pitfield [13] present the Evaluation and Logical Approach to Sustainable Transport Indicator Compilation (ELASTIC) framework, developed for identifying and selecting a small subset of key sustainable transport indicators. The framework proposes the development of a long list of potential sustainable transport indicators and systematic evaluation of each indicator for preliminary selection of key indicators (similar to the social 'hotspot') methodology. The evaluation is based on a Social Significance Index (SS_i) score, which uses goals and sub-goals with pre-set empirically derived weights. The framework further recommends the implementation of sensitivity analyses to select key indicators for consideration.

In agreeance on this approach, Zheng et al. [100] also put forward the use of sensitivity analyses to incorporate uncertainty modelling during the selection of key indicators. It is suggested that a baseline aggregated score, similar to the SS_i proposed in the ELASTIC framework, be calculated for each indicator, and then apply probabilistic modelling to determine a final aggregate score – representing the importance of each indicator relative to others. Additionally, Zheng et al. [100] submit that these key indicators be categorised and used in the social life cycle impact assessment phase (S-LCIA).

The subcategory assessment method (SAM), a characterisation method that evaluates subcategories to be used in the S-LCIA, was found to be the most common framework applied to categorise identified indicators in the literature [35]. The United Nations Environment Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC) [5] define two types of approaches for the characterisation of life cycle social impact assessments. For the first type, Type-1, 31 subcategories related to five main stakeholder categories (consumer, worker, local community, society, and value chain actors) shall be considered during assessments. UNEP and SETAC [5] state that failure to consider any of the categories or subcategories should be justified but also new subcategories may be included [35]. The assessment of these subcategories is generally conducted through qualitative performance reference points, providing thresholds to assess the inventory phase. An example of such a reference point in the pavement engineering field may be the environmental pollution generated as a result of pavement construction activities. A project that seeks to actively reduce pollution is accorded a higher score than a project which does not have strategies for pollution reduction. This example also illustrates the complex nature of social impacts and its correlation to environmental sustainability, where the increased pollution of the environment has a delayed but significant impact on the society, as seen through the exacerbation of climate change.

In applying the UNEP and SETAC SAM, it is noted that consideration of all subcategories is not always relevant to a specific industry. An example may be examining an S-LCA developed for the agri-food industry by Group Ageco and sustainable consultants QUANTIS, where certain subcategories were omitted and new subcategories included to better reflect the industry-specific social impacts and considerations [16].

For the second type of assessment, Type-2, impacts are evaluated according to their impact pathways, where a key indicator is translated into a midpoint- and subsequently an endpoint-indicator [69], similar to an LCA. UNEP and SETAC [5] provide seven midpoint-indicators (health, autonomy, safety, security and tranquillity, equal opportunities, participation and empowerment, and resource (capital) productivity) and three endpoint-indicators (human capital, cultural heritage and human well-being).

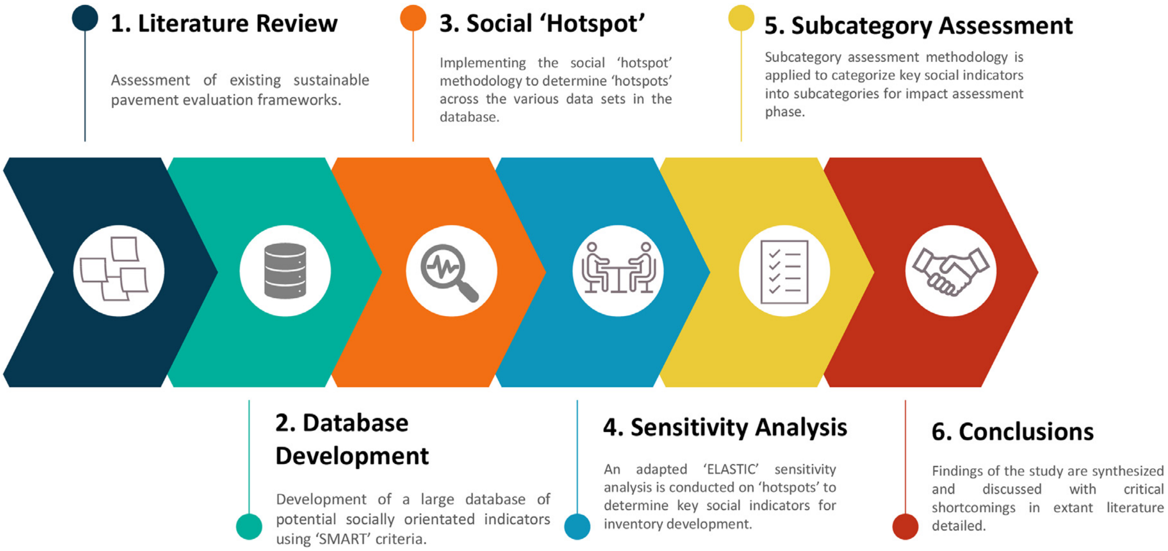
Structure of the study

This study aims to develop an S-LCI for pavements and provide a basis for an S-LCA, with South Africa used as a local scenario in line with recommendations to ensure consideration of regional challenges and goals [7,35,69]. This paper structure is illustrated in Fig. 1, and detailed as follows:

- First, an illustration of the existing landscape of pavement sustainable assessment frameworks is presented with the relationship among the three tenets of sustainability demonstrated;
- Second, social parameters among the frameworks are highlighted and used to develop a large database of possible key socially-oriented indicators. This is achieved by applying selection criteria adapted from the 'SMART' criteria [10]. The database is further supplemented by frameworks not specific to pavement development but sustainability in general, such as the Sustainable Development Goals (SDGs), and South African specific sustainable frameworks, such as the Broad-Based Black Economic Empowerment Act (B-BBEE);
- Third, the social 'hotspot' methodology is applied to the database to determine the hotspots across the various frameworks. This method is supplemented with an adapted SS_i [13] and represents the systematic evaluation and preliminary selection of key social indicators. The adaptation is realised through the inclusion of indicator frequency as proposed by Kühnen and Hahn [48] and Huarachi et al. [35] incorporating 'selection' bias;
- Fourth, sensitivity analyses are conducted on the adapted SS_i scores [13], enhanced using Bayesian-based Monte Carlo simulations to address uncertainty [100] and represents the final selection of key social indicators for pavement infrastructure provision;
- Fifth, the Type-1 SAM framework proposed by UNEP and SETAC [5] is applied to characterise the key indicators into 23 subcategories to be used during the S-LCIA phase. In general, the subcategories proposed by the UNEP and SETAC were considered but were adapted to better reflect the specific social impacts of pavement infrastructure provision. For instance, 'delocalization and migration' bear little relevance to pavement development or the responsibilities of roads authorities. However, 'road user and worker health and safety', 'community participation', 'local economic development and employment', and 'corruption' are very relevant to the field of pavement engineering, especially in South Africa, and are retained together with various other subcategories; and
- Sixth, the findings of the study are synthesised and discussed with critical shortcomings in extant literature detailed. Building on this synthesis, avenues for future research are provided. The paper is concluded by highlighting the main contributions.

Relevance to international audience

This study details the S-LCI for various categories and subcategories (i.e. inventory items) influenced by pavement infrastructure provision, using South Africa as a case study. The inventory utilises a large database of international and local sustainable frameworks with a focus on transportation infrastructure development and uses socially-oriented indicators as the key indicator input. Secondary indicators, such as 'pollution' and 'water use' which are predominantly environmental indicators, or 'value for money' which is predominantly an economic indicator, are also included due to their direct relation to social sustainability. These indicators are supplemented with South African specific sustainable indicators, such as 'fundamental economic transformation', to reflect regional challenges and goals. With relevant location-specific adjustments,



1. Literature Review

Assessment of existing sustainable pavement evaluation frameworks.

2. Database Development

Development of a large database of potential socially orientated indicators using ‘SMART’ criteria.

3. Social ‘Hotspot’

Implementing the social ‘hotspot’ methodology to determine ‘hotspots’ across the various data sets in the database.

4. Sensitivity Analysis

An adapted ‘ELASTIC’ sensitivity analysis is conducted on ‘hotspots’ to determine key social indicators for inventory development.

5. Subcategory Assessment

Subcategory assessment methodology is applied to categorize key social indicators into subcategories for impact assessment phase.

6. Conclusions

Findings of the study are synthesized and discussed with critical shortcomings in extant literature detailed.

Fig. 1. Research structure.

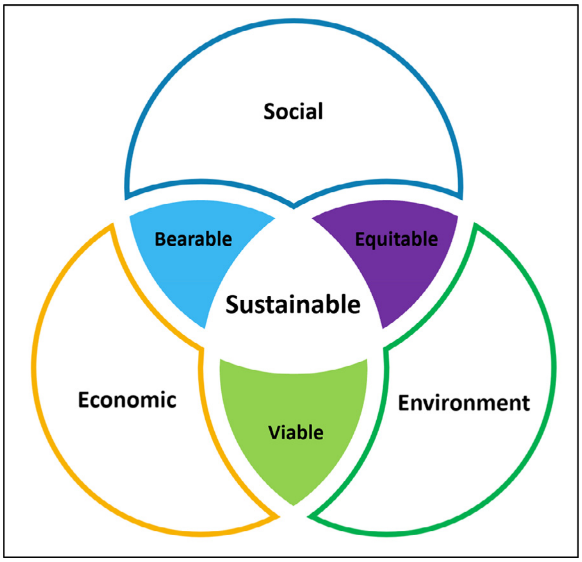


Fig. 2. The three spheres of sustainability (adapted from [1]).

this approach may be adapted and customized for any locale. This perspective follows the notion that sustainability is spatially dependent and influenced by local boundaries [7].

Literature review

Sustainability comprises three interconnected spheres that describe the relationships between economic, environmental and social aspects of the world we live in. When combined, they form a solid basis from which important decisions and actions can be made. Examples of such decisions include land use planning, water management systems, and construction and further extend to policy and law-making. When the concepts of the three spheres are combined with real-world situations, collective success is achieved. Fig. 2 illustrates this concept.

This study aims to assess various frameworks across the three spheres (or tenets) of sustainability related to pavement infrastructure provision, focusing on the social sphere, and its correlation to the economic and environmental spheres through the ‘bearable’ and ‘equitable’ overlapping sections.

Context and system description

An ever-growing number of governmental institutions and non-governmental organisations are embracing sustainability in their business models or product life cycles. This approach pursues the overarching goal of enhancing and balancing the economic, environmental, and social impacts of living and resource use.

In the field of S-LCA, a screening tool is believed to provide a meaningful way to prioritise efforts in evaluating the social impacts of business models or product life cycles [5]. In (environmental) LCAs, ‘default’ or industry average data are often used for common product background processes that make small individual (but possibly large cumulative) contributions to the impacts of a product over its life cycle [6,8]. A comparable method is employed in LCCAs to evaluate economic performances of alternatives. Through these evaluations, the processes or activities that contribute predominantly to the total impacts are identified, and these ‘hotspots’ become priorities for data refinement and further improvement [6]. A similar approach of ‘hotspot’ identification may be useful in the early stage development and standardisation of S-LCA frameworks. In S-LCAs, these ‘hotspots’ - represented by key social indicators - describe the unit processes of a product life cycle, are either a risk or an opportunity to contribute substantially to the total social impact of the product.

To achieve this, a top-down approach, proposed by the UNEP and SETAC Guidelines [5], is implemented in this study using various existing methods (i.e. LCCAs, LCAs, performance assessments, etc.) which assess pavement sustainability across the three tenets (i.e. economic, environmental and social). Considering the strong correlation among the tenets, the similarities may be used as guidance in the determination of social ‘hotspot’s and refined to key social indicators related to pavement infrastructure provision. To do so, each tool is individually assessed to develop a basis for applying the social ‘hotspot’ methodology. Additional tools and techniques which are not specifically developed for pavement evaluation but commonly implemented in South Africa to measure social impacts across various industries, such as EmpIAs are also included in this assessment. A flow chart of the process followed in developing a database of potential indicators using a top-down approach, to be used for further social ‘hotspot’ and subcategory assessments, is shown in Fig. 3.

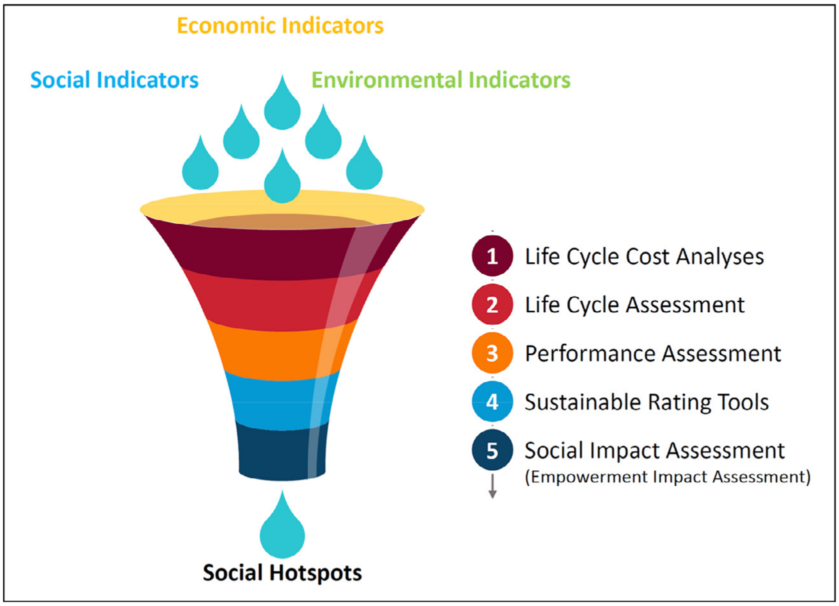


Fig. 3. Top-down approach to database development.

The following sections detail the main assessment specific indicators which have a direct relation to social sustainability.

Life cycle cost analyses

LCCAs are a well-established leading consideration in decision-making processes related to infrastructure projects and require little detailed introductions. This review will rather focus on the relation between LCCAs and S-LCAs. A key economic indicator which impacts on the social realm, used by most governmental organisations and institutions, is 'value for money' [95]. Value for money, viewed from a public perspective, is the most advantageous use of public funds to meet the quality, functionality and sustainability of a product or infrastructure it provides. An LCCA aims to evaluate alternative design solutions and determine the solution which provides the best value for the money spent over the analysis period of the product or asset [24]. Numerous costs need to be considered in an LCCA, including initial costs (e.g. purchase, acquisition and construction costs), fuel costs, operational, maintenance and rehabilitation costs, replacement costs, residual value estimates and finance charges. Furthermore, non-monetary benefits or costs, which do not have an objective way of assigning a dollar value to them, are also included as key considerations during the LCCA [71]. In the field of pavement engineering, these non-monetary costs may include 'educational opportunities' for and seeking the 'empowerment' of, targeted beneficiaries ensuring long-lasting 'jobs', among others. In addition to 'value for money' being a key socio-economic indicator, the additional non-monetary indicators are most closely aligned with social sustainability and focused on in this study. These non-monetary costs are further strongly impacted on by regional and industry-specific goals and reflect the need to develop S-LCIs on a spatially dependent platform. For instance, 'fundamental economic transformation', an indicator of significant importance in South Africa and discussed in later sections, is not necessarily relevant to other regions which do not have the same socio-economic objectives.

Life cycle assessments

An LCA is a structured methodology which enables the quantification of impacts of infrastructure-related processes such as operational, construction and maintenance to the environment over its full life cycle. An LCA aims to account for all processes, from the extraction of raw materials to the point at which those materials are returned to the environment at the end of life, often referred to as the "cradle to grave" concept [24].

The LCA can be further used to inform and guide decision-makers in industry, governments and non-government organisations for purposes including strategic planning, goal and priority setting and product and process design selection [24]. An LCA is particularly useful to determine the 'carbon footprint' of pavement processes or the amount of energy or water consumed during each process; but also allows for the measurement of other sustainable aspects such as overall waste generation [57] which both impact on the environment and subsequently the society that exists within that environment. This highlights the relation between environmental and social sustainability.

The forerunners of LCAs were originally developed in the 1960s and largely focused on analysing air, land and water pollutions from solid waste emissions. These tools were later expanded to include energy, resource use and pollution with a focus on consumer products rather than complex infrastructure projects [31,36]. Between 1990 and 2000, efforts shifted to standardising a full-fledged impact assessment method by the International Organisation for Standardisation (ISO) [40]. International attempts have been made to standardise an LCA procedure for pavement infrastructure projects, e.g. UCPRC [85], FHWA [24] and Highways England [33]; however, there are currently no governing agency- or government-issued guidelines for South Africa.

The LCA divides a pavement life cycle into six stages [88], briefly described below:

- Material Production - includes all processes used in the acquisition (e.g., mining and crude oil extraction) and processing (e.g., refining, manufacturing and mixing) of pavement materials;
- Design – processes that identify the structural and functional requirements of pavement infrastructure for specific conditions (i.e., subgrade, climate, traffic, existing pavement structure) together with the determination of the pavement structural composition and accompanying materials;
- Construction - includes all processes and associated equipment related to the construction of the initial pavement;
- Use Phase – the period during which the pavement is in service, carrying vehicles, interacting with the environment and providing lighting and other electrical services;
- Maintenance/rehabilitation – activities applied at various times during the service life of the pavement; and

- End of life – this stage refers to the final disposition and subsequent reuse, processing, or recycling of the pavement after it has reached the end of its useful life.

During each of these life cycle stages, environmental 'hotspots' have already been identified with strong empirical evidence to support the predominant environmental impacts and their relation to the economic and social tenets. The main environmental indicators which impact on social sustainability have universal acceptance and are not necessarily location-specific. These main indicators, relevant to the field of pavement engineering, may be summarised as various forms of 'pollution', including 'emissions', 'noise' and 'waste', as well as 'energy- and water-use', among others. These indicators set out both immediate and delayed social impacts.

Immediate impacts such as 'water use', are best described through an LCA example for pavements in South Africa presented by Blaauw and Maina [8]. In this example, it is shown how an alternative pavement structure may save as much as 338,560 litres of water per pavement kilometre construction. This water-saving equates to the water needs of a typical local settlement of 2000 people for one week per kilometre pavement built according to the South African Free Basic Water Policy [23]. Even though it is understood that much of this water used for construction will evaporate and return to the earth's surface in the form of precipitation or form part of the surface or groundwater flows, it is a long process and local depletion of water can occur rapidly. This is especially important in water-stressed areas and areas under threat of becoming drier due to climate change, which is common across most of the arid regions in South Africa [81].

Additionally, apart from the well-understood environmental emissions such as Carbon Dioxide which exacerbate climate change, various social emissions generated in the different pavement life cycle phases also have direct and often immediate social impacts. Emissions from pavement infrastructure provision which predominantly affect human health include SO_2, NOx, PM and VOCs. When these emissions are breathed in, they may cause nose, throat and airway problems, exacerbate asthma and in some cases cause cancer [94]. Zietsman and Khreis [101] argue that a child with asthma depends on a vehicle for transportation to a medical facility for treatment, where the vehicle spewing toxins, exacerbates the need for such treatment in the first place. This highlights the need to better understand the environmental impacts of pavement infrastructure provision and their social correlations.

Performance assessments

Performance assessments evaluate a pavement in terms of its intended design function and physical attributes required to meet that function [88]. Various methods are available globally to measure pavement performance, which includes rutting, roughness, texture, subgrade stiffness, deflection and visual indicators, among others, composite condition rating systems, pavement bearing capacity, specified material attributes (e.g. thickness, asphalt content, level of compaction, gradation) as well as methods to compare these attributes to expected design parameters through the use of, for instance, mechanistic-empirical design methodologies [45]. Performance assessments of pavements are a long-standing evaluation method and are built into most design and specification standards and as such, detailed descriptions are not provided in this study. Rather, following a similar approach previously implemented in evaluating assessment methodologies, the focus is on the performance indicators most closely related to social sustainability.

From a pavement performance perspective, the functional performance of a pavement is most closely aligned with social sustainability. Functional performance generally refers to the performance not related to the pavement structure, such as providing a smooth, 'safe', 'noise' reducing surface for use by both motorised and non-motorised road users year out. Functional performance, from a transportation perspective, extends to 'travel time', 'user cost' and 'congestion' as well as providing adequate 'pedestrian facilities' to ensure 'accessibility' of non-motorised road users and provide 'traveller information systems' during both construction and use phases. The South African Municipal Infrastructure Investment Framework (MIIF7) guidelines in part simplify the functional performance requirements to 'all-weather access to within 500 m of the dwelling' which may be compared to the functional performance required by the SDGs of an 'all-seasoned road within 2 km of the dwelling'.

Sustainable rating tools

The Federal Highway Association (FHWA) defines a sustainable approach to highways as helping decision-makers make balanced choices which consider environmental, economic and social aspects that will benefit current and future road users [24].

A sustainable rating tool (SRT) has been found to work well in this regard, allowing for the measurement of sustainable indicators of various pavement development processes and delineating the effects to a scale relevant to projects. An SRT generally contains a list of phases a project undergoes with sustainable features/goals for each phase where applicable. Sustainable indicators are assigned for each feature and the project receives a score indicating its level of sustainability [99]. An SRT tracks the three tenets of sustainability and provides performance targets against which project indicators are scored. SRTs are applied either in self-assessment or in the verification by an independent party [30].

A notable rating tool is a Leadership in Energy and Environment Design (LEED), which was developed by the US Green Building Council in 1993 and is reported to be the most commonly used green building rating system globally [49]. LEED has provided the basis for, and inspired the development of, SRTs in the transportation field [97,99]. Such rating tools include Greenroads, Envision, Green Leadership in Transportation Environmental Sustainability (GreenLITES), Infrastructure Voluntary Evaluation Sustainability Tool (INVEST), Livable And Sustainable Transportation (I-LAST), Sustainable Transportation Analysis and Rating System (STARS), and the Building Environmentally and Economically Sustainable Transportation-Infrastructure-Highways (BE^2ST-In-Highways) [73]. Additionally, the South African National Roads Authority SOC Ltd (SANRAL) has recently developed their SRT, the Sustainable Roads Forum (SuRF) rating tool.

Characterisation of sustainable rating tools

Generally, each SRT is environmentally dominated and considers the impacts of pavements on the natural environment in terms of material depletion, various forms of pollution and preservation of its natural state. Furthermore, water quality, affected by construction, and impacts of project alignment to natural water sources are unanimously accepted to be key indicators for sustainability. However, water use for construction purposes and its effects on the local community, for instance, is not considered throughout. It is difficult to justify the use of large volumes of treated water in relatively arid areas common in South Africa, where the local population struggle to meet their own daily water needs [81].

In the case of social impacts, SRTs tend to focus on mobility in terms of requirements for park-and-ride lots and bus lanes and further focusing on user safety. The SRTs do not generally consider the effect of a project on the local community and the opportunity of employment through implementation of labour-intensive construction methods as an example, with SuRF being the only SRT considering these indicators. Greenroads [29] and STARS [80] together with SuRF are the only three SRTs for which the implementation of social indicators is compulsory, with the remaining SRTs providing indicators which address social considerations but are not required to receive accreditation.

When measuring social impacts, the target beneficiaries are typically those who will be directly empowered through sub-contracting, temporary jobs, and education. The provision of jobs for these beneficiaries also tend to be limited to the construction phase and long-term employment opportunities are not focused on in these assessments. An ideal socio-economic impact of pavements may be described as reaching unemployed beneficiaries, providing them with jobs and education/training opportunities to ensure sustainability of their future employment.

The SRTs found in the literature are commonly developed for implementation during the conceptual and design phases. Thus, the SRTs typically do not specify performance metrics to evaluate pavements, with only BE^{2}ST [20] utilising the International Roughness Index metric. Considering performance, GreenLITES [28] promotes the use of bioengineering techniques (e.g. organosilanes) to enhance material properties and increase the durability of pavement structures but lacks the functionality to quantify the relationship between the indicator and sustainable pavement performance.

Only one rating system, Envision [39], considers the impacts of climate change from a risk perspective and provides indicators which focus on enhancing the climate resilience of pavement infrastructure in the face of future impacts. Envision does not consider the impacts of climate change on local communities and how pavement development may exacerbate those impacts. Further risks related to the community, market interference, etc. are not included in any of these assessments.

SRTs are often developed using a bottom-up approach making them spatially dependent and hard to implement in different locations. They are developed based on practices perceived to be sustainable, evaluating infrastructure based on outcomes rather than quantitatively measuring impacts of achieving those outcomes. Criteria are limited to those that are standardised and well understood, often neglecting important criteria which are difficult to measure [44].

A review of the various SRTs reveals that all tools support the implementation of sustainable best practices. Each system, however, differs in its method of evaluation, whether through comparisons to base designs, quantitative methods, the use of expert opinions in the form of third-party validation or self-assessments. Regardless of the methodologies, all systems pursue the same objective.

Social impact assessment

Rights-based approaches to sustainable development have been promoted since the 1990s, but little progress has been made in quantifying the effectiveness of these approaches. An SIA is one method used to measure social sustainability, by analysing, monitoring and managing the desirable and undesirable social consequences of planned interventions (policies, programs, projects etc.), and any social changes invoked by those interventions. The primary objective of an SIA is to bring about a more sustainable and equitable human environment [90]. The objective of an SIA applied in South Africa is to optimise the process deliverables in addition to the product deliverables in a way that balances the initial investment premium and long-term social benefits.

An SIA is best described as an overarching framework that encompasses the complex evaluation of a variety of human impacts, having strong links with a range of sub-fields involved in the assessment [90]. Given the multiplex nature of social considerations, it is difficult to develop a generic framework robust enough to assess unknown future situations. To circumvent this problem, an SIA could be developed to become situational, location-specific and time-dependent. It is then important to clearly define the framework boundaries in which the assessment is to be applied. Nicaise [59] states that an SIA should be considered as legally required and not optional, be ex-ante in nature, and require the participation of stakeholders for continual improvement and development.

From the authors' experience, the development and application of high-quality SIAs are demanding, time-consuming and expensive. A balance is, therefore, needed between the investment required and the importance of the measures that are assessed [59]. The statistical data, analytical capacity and stakeholder participation required for a good SIA cannot be developed overnight and should be viewed as a living framework subject to continuous evaluation and improvement.

In South Africa, few attempts have been made to develop SIAs or any other empowerment models for that matter. Most worthy of note and applied by the Provincial Administration of the Western Cape, Department of Transport and Public Works since 2000 are the B-BBEE Act and the EmpIA protocol developed.

Broad-based black economic empowerment

The B-BBEE Act of 2013 aims to "promote the achievement of the constitutional right to equality, increase the broad-based and effective participation of black people in the economy… and establish a national policy on broad-based black economic empowerment to promote the economic unity of the nation" [4].

Key objectives of the B-BBEE Act relevant to this study are [4]:

- "promoting economic transformation in order to enable meaningful participation of black people in the economy;
- achieving a substantial change in the racial composition of ownership and management structures and in the skilled occupations of existing and new enterprises;
- increasing the extent to which communities, workers, cooperatives and other collective enterprises own and manage existing and new enterprises and increasing their access to economic activities, infrastructure and skills training;
- increasing the extent to which black women own and manage existing and new enterprises, and increasing their access to economic activities, infrastructure and skills training;
- promoting investment programmes that lead to broad-based and meaningful participation in the economy by black people in order to achieve sustainable development and general prosperity; and
- empowering rural and local communities by enabling access to economic activities, land, infrastructure, ownership and skills".

These objectives can generally be summarised by the overarching objective of initially 'economic transformation', later 'radical economic transformation', and more recently 'fundamental economic transformation'.

Fundamental economic transformation in infrastructure development

'Fundamental economic transformation' is observed and experienced by many as one of the leading objectives to achieve in South Africa. As an example, it is ranked by SANRAL in its Horizon 2030 Vision Statement as one of their 10 long-term objectives. This objective is most practically implemented using the Preferential Procurement Policy Framework Act [66] and the Preferential Procurement Regulations [67], which requires organs of state to award contracts based on preferential procurement through assigning preference points for predominantly B-BBEE beneficiaries. For the majority of SANRAL projects, the relevant preference point system followed is detailed as follows [67]: "for contracts with a Rand value above R50,000,000.00, a maximum of 10% points may be allocated for specific (preference) goals, provided that the lowest acceptable tenderer scores 90 points for price". For projects below this threshold, an 80/20-point system is used, and applicable to many SANRAL pavement projects.

Effective implementation of these point systems allows for projects to be considered favourably given the specific socially orientated goals and, if the specific goals are adhered to by the tenderer, the tenderer may increase their price substantially compared to a tenderer who does not meet the social goals. The Standard for Infrastructure Procurement and Delivery Management (SIPDM) states that "not less than 50% of the points shall be allocated to BEE goals". These point systems can carry a price premium as high as 25% [77]. Anthony [2] reports that government procurement may account for as much as 21% of the total Gross Domestic Product of South Africa, which, if combined with a 25% price premium, may have detrimental impacts on the economy. The long-term effects of such procurement are not well documented and the impacts on 'value for money', a key indicator of both the World Bank and the South African Treasury, are yet to be understood [42].

A prominent risk of fundamental- or 'radical'-economic transformation in South Africa is 'radical economic robbery'. Radical economic robbery is a term used by the President of South Africa during the 2020 State of the Nation Address (SONA, 2020) to refer to the 'so-called' business forums who demand a share from any construction projects often located within proximity to where the members live. What has largely fuelled the increasing risk of these business forums or 'construction mafia' are the misperceptions regarding beneficiaries in the South African public, who believe that fundamental economic transformation gives them automatic access to contractual participation without being subjected to competitive bidding or having to contribute resources, work and guarantees. Large scale projects affected include the N2 Wild Coast Road Construction project and the R2.4-billion German oil storage investment project in Saldanha, among countless smaller projects [12].

Western cape empowerment impact assessment

The EmpIA protocol developed by the Provincial Administration of the Western Cape, Department of Transport and Public Works, in 2000, was one of the first attempts in South Africa at measuring empowerment impacts of technical and managerial choices in transportation infrastructure projects and was applied on several projects in the Western Cape [93]. After initial implementation, the model was reviewed and outcomes evaluated, which signified a need for a revision. This revision included consideration of employment impacts post-construction as opposed to only focusing on temporary employment during the design and construction phases. Additionally, the need to focus on the broader concept of social sustainability was observed compared to merely considering initial empowerment impacts.

The EmpIA protocol focuses on five key social impacts, namely [93]:

1. Labour enhanced task opportunities;
2. Local economic development opportunities;
3. Local plant/material resources opportunities;
4. Beneficiary identification and quantifying needs; and
5. Skills identification and training.

The target beneficiaries of this framework are previously disadvantaged individuals with a specific unemployed requirement for project involvement. Beneficiaries must generally be local residents and attention is given to black women and youth as prescribed by the B-BBEE Act.

The protocol incorporates indicators such as jobs created per unit investment, beneficiaries reached, and additional support provided. The original protocol does not provide the facility to determine the increase in project cost as a result of implementing empowerment compared to alternatives nor does it quantify the socio-economic impact of implemented initiatives. The EmpIA analysis tool [93] did indeed introduce the indicator of allowable cost premium above which no further uneconomical labour absorption or local resourcing is justified. What such frameworks lack is the ability to evaluate the long-term impacts of technical and managerial choices and determine if the premium investment on empowerment has indeed assisted in reaching long-lasting sustainable goals (such as e.g. reflected in the National Development Plan [58]).

Uncertainty in social life cycle assessments

Costa et al. [15] state that in applying an S-LCA, the key challenges include the absence of standardised inventory data, inconsistent system boundaries and difficulty in developing methodological frameworks. Additionally, Costa et al. [15] state that the leading challenge is a lack of fully performing uncertainty analyses, an activity strongly recommended by UNEP and SETAC guidelines and various researchers [15,62,98]. Zheng et al. [100] conducted a literature review on the implementation of uncertainty analyses in S-LCAs, particularly in the field of pavement engineering, and found that no studies have incorporated uncertainty into S-LCA frameworks. In addressing this shortcoming, Zheng et al. [100] proposed a methodology for incorporating uncertainty into pavement S-LCAs using an analytical hierarchy process (AHP) supplemented by Monte Carlo simulations for sensitivity analyses. An AHP is a structures technique for organising and making decisions in complex environments where numerous variables or criteria need to be considered in prioritisation of key considerations including indicators. Zheng et al. [100] used the AHP to develop initial scores and weights to be used to calculate a final sustainable score for a project. Monte Carlo simulations were then implemented on the baseline scores to convert the sample into random scores with uniform distributions, and in so doing reduced uncertainty. Zheng et al. [100] were able to successfully determine a final aggregated social sustainable score for a project with a 95% confidence level.

Probabilistic modelling

A variety of probabilistic models are available which have been successfully implemented in the field of sustainable pavement engineering aiming to capture uncertainty within datasets. Prominently used models include Bayesian analyses and Monte Carlo simulations [92].

Bayesian analysis

Bayesian analysis is a statistical technique which endeavours to estimate underlying distribution parameters based on an observed distribution [26]. The method begins with a 'prior distribution' that has no limitations and may even be non-Bayesian observations. The prior is considered the value that a statistician would expect from the outcome without having any evidence or data to support it. Data is then collected from various sources (e.g. trials, experiments, field data, expert opinions, literature, etc.) to form the observed distribution. Probability is then calculated as the likelihood of the observed distribution, which is a function of the underlying distribution parameters. Multiplying this likelihood with the prior distribution and normalising the data results in a unit probability over all possible values known as the posterior distribution [34].

Bayesian analysis has been commented on to be controversial given the validity of results depends on how valid the prior distribution is - which cannot be statistically assessed [68]. However, the method has successfully been implemented in numerous pavement engineering related studies, especially where poor-quality data is available [92].

When applied in the pavement engineering field, Bayesian analyses tend to be used for risk analysis [19,41,51,74,76], with few studies focusing on its implementation in sustainable evaluations. Tymošenk and Golovach [84] applied Bayesian networks to study the sustainable elements associated with agriculture and rural development of territorial communities, focusing on social and economic impacts. The study obtained data through questionnaires seeking to obtain data relevant to the study objective, of which certain factors are believed to increase the capacity for sustainable development of the rural territory in the future. The social status of respondents was not focused on local residents but rather experts were consulted, which is a common trend among other studies [63,64]. The results were analysed using a simple Bayesian belief network and determining the predominant factors affecting the sustainable development of the communities.

Monte Carlo

Monte Carlo simulations are computational algorithms that use repeated random sampling to determine numerical results and solve problems that are often deterministic, relying on data input and distribution definition. A great strength of Monte Carlo simulations is that they can be used to draw data from a distribution where, for example, the only thing known of the distribution is its density or frequency [89]. This is particularly useful in concepts which are difficult to quantify, such as sustainable impacts relevant to pavement infrastructure. Similar to the use of Bayesian analyses, Monte Carlo Simulations are more commonly applied in risk- [52,56] or environmental impact-assessments [47], and more recently proposed for use in S-LCA frameworks [13,100].

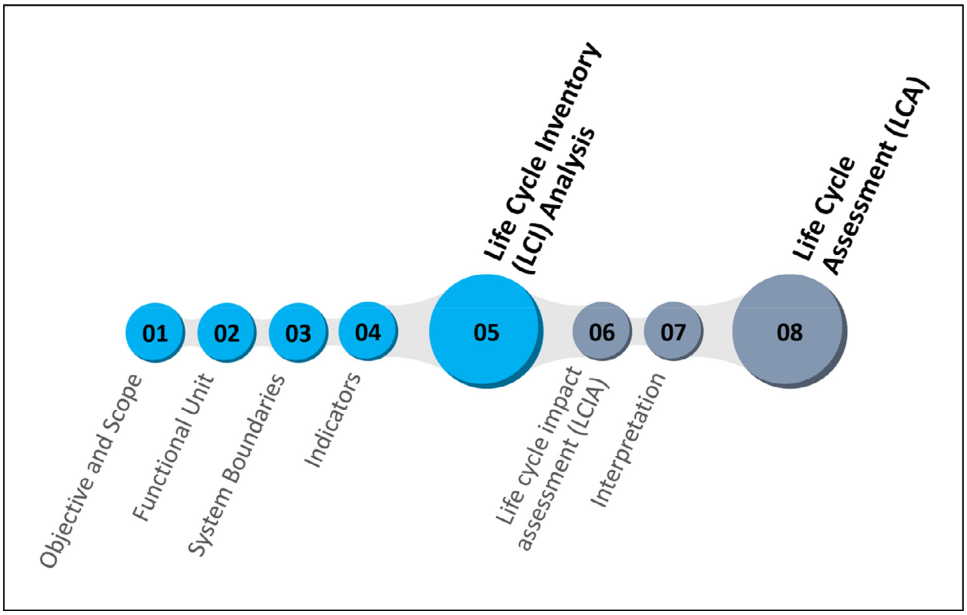


Fig. 4. UNEP and SETAC methodological framework for S-LCA development.

Monte Carlo simulations are further widely used in industries such as marketing, customer services and health care to process chance and uncertainty, more specifically either filling gaps in data of social surveys of population groups difficult to reach (e.g. the elderly) or developing 'average' behavioural trends of those population groups [25]. This is especially beneficial in evaluating the uncertainty in sustainable assessments where the impacts perceived most influential are uncertain. In applying Monte Carlo simulations, the selected distribution may significantly affect results. Commonly used distributions include lognormal distributions for quantifying uncertainty in unit cost [83], normal distribution for uncertainty in construction costs [82] and triangular distributions in uncertainty where little information is available [96]. Zheng et al. [100] proposed the use of uniform distributions when uncertainty is analysed among social impacts and is the distribution selected for use in this study. The study further aims to include Bayesian principles in defining an expected prior obtained through the social 'hotspot' methodology and adapted baseline SS_i score.

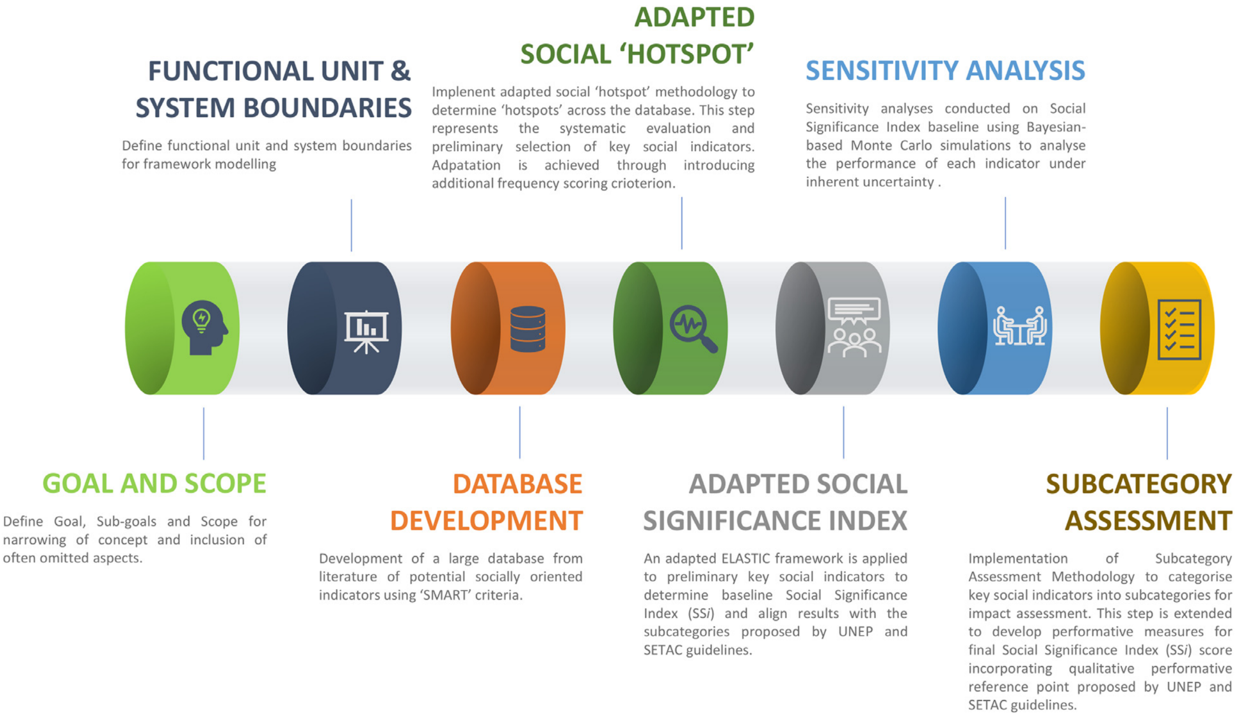
Methodology

The methodological framework implemented in this study follows the guidelines proposed by UNEP and SETAC and is structured similar to ISO 14040 [40] for the development of an LCA. As this study only aims to develop an LCI, certain steps of the UNEP and SETAC framework are not performed. Fig. 4 shows the simplified UNEP and SETAC framework, with the steps which are implemented in this study highlighted in blue (steps 1 to 5), and the steps not performed highlighted in grey (steps 6 to 8).

Proposed methodological framework

As standardisation has not yet been achieved to implement this general framework, a framework consisting of seven steps for S-LCI development is proposed in this study combining the steps most commonly included and successfully applied in the literature. This proposed framework is detailed below and illustrated in Fig. 5.

1. **Define goal, sub-goals and scope:** In extending the general LCA framework requirements of goal and scope definition, additional sub-goals included in the ELASTIC framework [13] are included to create a link with the subcategories proposed by UNEP and SETAC guidelines [5]. The sub-goals provide further decomposition through the specification of selection criteria adapted from the 'SMART' criteria [10], summarised in Table 1.
2. **Functional unit and system boundaries:** The functional unit (FU), constituting the reference unit used to measure the performance of indicators, is often easily defined in typical LCA studies. However, when applied to S-LCAs, it may not be as simple and linking results to the FU is often difficult to achieve [5]. However, the UNEP and SETAC guidelines stress the importance of creating a set of FUs and accompanied system boundaries, and state that in situations where alternatives are to be compared, the FU must be based on a function rather than an item or product. System boundaries determine which unit processes along the product life cycle are included in the system being assessed [5].
3. **Database development:** Assembling a large database of potential sustainable pavement indicators from renowned sources was conducted following the UNEP and SETAC guidelines together with proposed methodologies detailed in the literature. The International Organisation for Standardisation 14040 [40] indicator data quality requirements are satisfied using peer-reviewed, local and international sources which have successfully been implemented in public and private practices. 'SMART' criteria are further introduced to reduce the database to relevant indicators linked with the ELASTIC sub-goals, providing a pathway to the subcategories proposed by UNEP and SETAC.
4. **Adapted social 'hotspot' methodology:** This step seeks to implement an adapted social 'hotspot' assessment to determine the 'hotspots' across the socially-oriented database and represents the systematic evaluation and preliminary selection of key social indicators. The adaptation is achieved through applying an additional frequency scoring criterion proposed by Kühnen and Hahn [48] and Huarachi et al. [35] incorporating 'selection' bias. The frequency scoring refers to the number of times an indicator appears among datasets and is used to enhance the ELASTIC *SSi* score and uncertainty analyses in following steps.
5. **Adapted social significance index:** The Elastic framework is adapted and implemented in this study predominantly to determine the baseline *SSi* score [13] for each indicator to be used as input for sensitivity analyses. The adaptation is realised through including the frequency score determined from the social 'hotspot' assessment.
6. **Sensitivity analysis and key social indicator selection incorporating uncertainty:** This step seeks to conduct sensitiv-



GOAL AND SCOPE

Define Goal, Sub-goals and Scope for narrowing of concept and inclusion of often omitted aspects.

FUNCTIONAL UNIT & SYSTEM BOUNDARIES

Define functional unit and system boundaries for framework modelling

DATABASE DEVELOPMENT

Development of a large database from literature of potential socially oriented indicators using 'SMART' criteria.

ADAPTED SOCIAL 'HOTSPOT'

Implenent adapted social 'hotspot' methodology to determine 'hotspots' across the database. This step represents the systematic evaluation and preliminary selection of key social indicators. Adpatation is achieved through introducing additional frequency scoring crioterion.

ADAPTED SOCIAL SIGNIFICANCE INDEX

An adapted ELASTIC framework is applied to preliminary key social indicators to determine baseline Social Significance Index (*SSi*) and align results with the subcategories proposed by UNEP and SETAC guidelines.

SENSITIVITY ANALYSIS

Sensitivity analyses conducted on Social Significance Index baseline using Bayesian-based Monte Carlo simulations to analyse the performance of each indicator under inherent uncertainty .

SUBCATEGORY ASSESSMENT

Implementation of Subcategory Assessment Methodology to categorise key social indicators into subcategories for impact assessment. This step is extended to develop performative measures for final Social Significance Index (*SSi*) score incorporating qualitative performative reference point proposed by UNEP and SETAC guidelines.

Fig. 5. A proposed methodological framework for S-LCI development.

Fig. 6. Heat map of common 'hotspots' derived from a reduced database.

Table 1
Adapted SMART indicators [10].

Importance	Measurable	Attainable	Timely	Interpretable	Isolatable
Indicators should be considered important to the relevant stakeholders.	Each indicator should be measurable and hence requires a precise definition.	The indicator must be attainable at a reasonable cost using an appropriate collection method.	An indicator needs to be collected and reported at the right time to influence many management decisions.	Indicators should be easily interpretable to the people who will use the data.	Key indicators need to be easily isolatable and not create confusion through comparison to other indicators.

ity analyses on the baseline *SSi* scores obtained from the previous step and is achieved through incorporation of Bayesian-based Monte Carlo simulations to analyse the performance of each indicator under inherent uncertainty [100]. A final *SSi* score is determined and used as a performative reference baseline for use in the SAM analysis.

7. **Subcategory assessment method:** In the final step, a Type-1 SAM is applied to the key social indicators identified from Step 6 and develop performative measures and allow for final *SSi* scoring as proposed by Zheng et al. [100]. The final *SSi* score is further aligned to the qualitative performance reference point principle proposed by UNEP and SETAC guidelines [5]. The performative measures may be used to develop social life cycle impact assessments and interpretation, completing the framework for an S-LCA.

Goal, sub-goals and scope

Goal

The proposed framework utilises and evaluates a long list of indicators to identify a subset that maximises desirable qualities. As such, the overarching vision is pre-defined [13]. The goal of this study is to provide an inventory for key sustainability indicators related to the development and management of pavement infrastructure in South Africa with an emphasis on the social tenet. ISO standard 14040 [40] was used to develop this inventory. The inventory is intended to act as a building block on which to improve and develop further life cycle inventories where specific social consideration is provided to provide a holistic sustainable life cycle assessment model for pavement infrastructure in South Africa.

Sub-goals

Following the guidance of the ELASTIC methodology [13], three adapted specific and non-changing sub-goals are prescribed, namely:

i. Maximise the methodological quality of indicators;
ii. Maximise the relevance of indicators to the concept of sustainable pavements; and
iii. Maximise the importance of indicators to the concept of sustainable pavements, achieved through an adapted frequency analysis proposed by Kühnen and Hahn [48] and Huarachi et al. [35] (this is an additional sub-goal used to supplement the existing ELASTIC framework).

These goals allow for a narrowing of the vision but are still broad enough to allow for evaluation of indicators using quantifiable criteria, shown in

Scope

The study considers a cradle-to-grave scenario for the construction, maintenance, rehabilitation and salvaging of pavement infrastructure, and is representative of any pavement system in South Africa. The model provides key social indicators focused on health, safety, environmental, socio-economic and empowerment impacts of pavement infrastructure.

Functional unit and system boundaries

The FU used for this analysis is a 7.2 m wide, 1 km long pavement structure. For analysis purposes, the focus will be given to the functional performance and direct social impact of background processes, detailed throughout literature, required to provide the pavement infrastructure. The system boundaries include the following steps:

1. Raw material extraction;
2. Material processing and production;
3. Construction;
4. Use phase;
5. Maintenance; and
6. Demolition

Database development

For the application of the proposed framework in South Africa, an initial long list of 1,352 sustainable transport indicators were identified from 25 renowned local and international sources. These sources include relevant sustainable pavement assessment frameworks described in this study and additional assessment frameworks commonly applied in the industry such as the Sustainable Development Goals. In applying the adapted 'SMART' criteria listed in Table 1, the database is reduced to indicators which are socially focused. As previously discussed, environmental and economic indicators which have either direct or indirect social consequences are retained, reducing the initial long list of 1,352 indicators to 366 socially relevant indicators. These indicators are used for further analyses during this study. A summary of the database is shown in Appendix A, with detailed information withheld due to proprietary relationships.

Table 2
Frequency of indicators derived from a reduced database.

Social 'Hotspots'	Frequency
Emissions	19
Value for Money	19*
Climate Change	19*
Fundamental Economic Transformation	19*
Safety (Road User & Worker)	18
Water use and pollution	17
Noise	16
Health (Road User & Worker)	16
Community Participation	15*
Air Quality	13
Provision of Pedestrian Facilities	12
Jobs	12
Travel Time	11
Accessibility	11
Local Economic Development	11
User Cost	10
Education	9
Energy use	8
Pollution	8
Provision of Traveller Information Systems	7
Congestion	6
Resilience	6
Empowerment	5

* 'Hotspot' frequency altered to reflect importance in South Africa

Results

Adapted social hotspot methodology

As various datasets developed by numerous researchers were used for this study, a range of words and phrases have been utilised throughout which ultimately have the same implication, such as 'water quality' and 'water pollution'. To obtain the social 'hotspots' from the reduced database, a word heat map was drawn on to analyse and identify the words or phrases most listed. The additional frequency step proposed by Kühnen and Hahn [48] and Huarachi et al. [35] is also applied to these 'hotspots', representing the preliminary key social indicators. It is noted that the frequency of certain 'hotspots' has been altered to better reflect their importance to the South African pavement engineering field and current global political landscape, through applying the principle of 'survival' or 'selection' bias.

Selection bias

Selection bias refers to the logical error of concentrating only on indicators which made it past the selection process and overlooking those that did not. An example of this would be considering the 'climate change' indicator, which among others, did not receive a high enough frequency score (i.e. 3) to be considered a 'hotspot' as it is omitted in most data sets used to develop this database.

The results of the social 'hotspot' methodology incorporating selection bias are shown in Figure 6, providing 23 'hotspots', with the frequency results detailed in Table 2.

Adapted ELASTIC social significance index

In preparation for sensitivity analyses and uncertainty modelling, an adapted ELASTIC SS_i is applied to determine the baseline SS_i scores of each indicator. This adaptation is realised by including the frequency step previously discussed to represent the 'Importance' of the indicators, combined with the 'Relevance to sustainable pavements' and 'Methodological quality' sub-goals of the ELASTIC framework.

For the 'Importance' criterion, the score is calculated as the indicator frequency divided by the highest indicator frequency (i.e. 19) normalised to a score out of 5. Secondly, the 'Methodological quality' sub-goal is scored on a Likert scale using the scoring matrix shown in

Table 3
Baseline SS_i Scores.

Relevance to sustainable pavements	Key Social indicators	Baseline SS_i
Liveable Streets and Neighbourhoods	Noise	0.92
	Air Quality	0.80
	Travel Time	0.74
	Congestion	0.65
	Resilience	0.60
Protection of the Environment	Emissions	0.94
	Water use and pollution	0.96
	Energy use	0.83
	Pollution	0.78
	Climate Change	0.91
Equity and Social Inclusion	Accessibility	0.68
	Local Economic Development	0.94
	Fundamental Economic Transformation	0.87
	Community Participation	0.87
Safety	Safety (Road User & Worker)	1.14
	Health (Road User & Worker)	1.14
	Provision of Pedestrian Facilities	1.06
	Provision of Traveller Information Systems	0.93
Vibrant and Efficient Economy	Jobs	0.86
	User Cost	0.94
	Value for Money	0.75
	Education	0.79
	Empowerment	0.71

Appendix B and sub-goal weights shown in Appendix C. The 'Relevance to sustainable pavements' sub-goal is not scored for individual indicators in this study and the weights determined by Castillo and Pitfield [13], also shown in Appendix C, are applied. Indicators are then numerically aggregated employing a Simple Additive Weighting (SAW) approach and an adapted SS_i score is calculated for each indicator, where the best performing indicator is the one with the highest total weighted sum score. The SS_i is calculated as follows [13]:

$$SS_i = \sum_{j=1}^{n} s_j^a (g_k w_j) + II \text{ for all } j = 1, 2, 3, \dots, \text{ and } k = 1$$

Where:

SS_i is the overall weighted performance score of indicator *a;*

g_k is the importance weight of sub-goal *k;*

w_j is the importance weight of criterion *j;*

s_j^a is the normalised outcome score for indicator a on criteria *j;* and

II is the performance of indicator a determined by the frequency (representing the adaptation).

The baseline SS_i score results are shown in Table 3. Additionally, the 'Relevance to sustainable development' sub-goals are also shown in Table 3.

Sensitivity analyses incorporating uncertainty

The baseline SS_i scores from the previous step are used as key input for sensitivity analyses. The ELASTIC methodology provides weightings for each indicator sub-goal and criterion which were used to determine the baseline scores. These weights, influenced by the goal and scope of this framework, are further used for sensitivity analyses to determine their impact on key social indicator selection. This approach follows the proposal of UNEP and SETAC guidelines [5] stating 'it is recommended that S-LCA studies attempt to characterize the sensitivity of their data due to system boundary decisions'.

Implementing these weightings and the baseline scores, a sensitivity analysis was conducted using Bayesian-based Monte Carlo simulations in which 50,000 outcomes were modelled using a uniform distribution [100]. The model accounted for every possible scoring scenario and provided results for the indicators which consistently performed well-given input changes and uncertainty. The results of the simulations are summarised in Table 4. Typical results of the simulations are shown in Appendix D.

Subcategory assessment method

In this study, a Type-1 SAM analysis is applied to characterise indicators into relevant impact categories. In applying the Type-1 SAM analysis, UNEP and SETAC guidelines require that the impact categories, which should correspond to the goal and scope of the study, represent the key social issues of interest regarding the stakeholders affected. It is noted that this approach in impact category definition may vary from the commonly understood and accepted impact categories used in LCAs, such as 'global warming'. This is largely due to a lack of sufficient experience to determine universally accepted impact categories for S-LCAs as the cause-effect relationships are not simple enough or not known with enough precision for confident modelling [5].

In applying the Type-1 SAM analysis, relevant indicators and their SS_i scores are aggregated into subcategories according to the overall indicator objective related to the resulting end-category. This allows for each impact category to carry a certain weight determined from previous steps, which ultimately contribute to social sustainability as proposed by Zheng et al. [100].

To determine the final aggregated score, or Social Sustainable Score (SS_s), each impact category is scored on a Likert scale (between 1 to 5) and the score is multiplied by a normalised grouping weight (obtained as the sum of the indicator weights grouped into subcategories). The subcategories, corresponding weights and endpoint impact categories are shown in Table 5.

Using the final SS_s determined in Table 5, where a maximum of 100 points is achievable, a project's sustainability may be evaluated by comparing the score against a set of proposed benchmarks, shown in Table 6. The proposed benchmarks have been determined as 'unsustainable', where sustainable interventions are not implemented, 'business as usual', where only commonly accepted sustainable interventions are implemented, and 'silver, 'gold' and 'evergreen' where an increasing amount of sustainable interventions are implemented above the norm.

Projects may be scored either through self-assessment or third-party validation.

Worked example

To demonstrate the use of the impact categories developed in this study, a worked example is provided based on a case study previously assessed using an EmpIA [93]. This case study is firstly evaluated based on only the social indicators utilised in the EmpIA and reevaluated incorporating broader social considerations as proposed in the S-LCI of this study.

The case study considered the construction and upgrading of 2 km of the sidewalk and the demarcation of taxi embayment on the main access road to the informal part of Nkqubela, a settlement in the Western Cape. The project aimed to increase the safety of non-motorised users and access to public transport. Since the ownership of vehicles in the area is very low, the use of public transport is dominant. The project value was R3 million ($200,000) and emphasis had been given to empowerment through labour enhancing construction methods.

Applying the EmpIA, local beneficiaries were identified favouring black women, youth and disabled individuals. The beneficiaries were identified through community engagement and discussions with community leaders on the local needs. The literacy and training of each beneficiary were assessed ranging from unskilled to skilled, and the beneficiaries were assigned to certain construction tasks according to their abilities. The methods of construction for each task were adapted to increase labour inputs and meet the skill levels of the beneficiaries. Additional training opportunities were evaluated, and it was determined

Table 4
SS_i-Baseline and -Monte Carlo Simulation Comparison Results.

Social sustainable indicator	SS_i - Baseline	SS_i – Monte Carlo simulations	Position change compared to baseline
Safety (Road User & Worker)	1.14	1.03	-
Health (Road User & Worker)	1.14	1.00	-
Provision of Pedestrian Facilities	1.06	0.93	-
Emissions	0.94	0.86	↑
Climate Change	0.91	0.86	↑
Provision of Traveller Information Systems	0.93	0.84	↑
Water use and pollution	0.96	0.83	↓
Fundamental Economic Transformation	0.94	0.81	↓
Value for money	0.94	0.81	↓
Community Participation	0.87	0.75	↑
Local Economic Development	0.87	0.75	↑
Noise	0.92	0.74	↓
Air Quality	0.80	0.69	↑
Jobs	0.86	0.69	↓
Accessibility	0.68	0.67	↑
Energy use	0.83	0.67	↓
Pollution	0.78	0.67	-
Travel Time	0.74	0.66	↑
Congestion	0.65	0.66	↑
Resilience	0.60	0.66	↑
User Cost	0.75	0.66	↓
Education	0.79	0.64	↓
Empowerment	0.71	0.57	↓

Table 5
Proposed Impact Categories.

Impact category	Subcategory	Score*	Subcategory weight
*To what extent do you agree with the following statements (1 = strongly disagree; 5 = strongly agree) If the project has not made consideration for a performative measure, a score of '0' is awarded.			
1 Pollution	A life cycle assessment has been conducted and reduction of Emissions, Waste, Energy use, and Water contamination has been achieved.		4.29
2 Socio-economic Impact	The project achieves Fundamental Economic Transformation through, inter alia, providing Educational opportunities for, and seeking the Empowerment of, targeted beneficiaries ensuring long-lasting Jobs.		3.15
3 Safety	There are good systems in place to ensure Health and Safety of workers, motorised and non-motorised road users.		2.26
4 Functional Performance	The project ensures a reduction in Travel Time, User Cost and Congestion through both construction and use phases.		2.3
5 Functional Performance	Adequate Pedestrian Facilities have been provided to ensure the Accessibility of non-motorised road users.		1.83
6 Climate change	The predicted impacts of local Climate Change have been considered and vulnerable pavement systems (including local communities) have been identified. Pavement Resilience has been increased and pavement construction and maintenance impacts on local communities decreased.		1.74
7 Local economic development	The project achieves Local Economic Development through promoting and favouring Community Participation and Labour Enhanced Construction Methods.		1.71
8 Functional Performance	Traveller Information Systems are provided during construction and use phases.		0.95
9 Financial Performance	The project ensures good Value for Money.		0.92
10 Pollution	Efforts have been made to reduce Noise during construction and use phases.		0.85
SS_s **Total (100)**			

Table 6
Proposed sustainable levels for pavements in South Africa.

Weighted score	Sustainable level
<50	Unsustainable
50-60	Business as usual
60-75	Silver
75-90	Gold
>90	Evergreen

that increased awareness of life skills, diseases, construction health and safety, and construction administration were areas to focus on.

The results of implementing the EmpIA were that the project employed roughly 55 previously unemployed local beneficiaries consisting of unskilled, semi-skilled and skilled individuals with a composition favouring black women, youth and disabled individuals sourced from the local community. 30% of the project value was spent on labourer fees by promoting labour enhancing construction methods and approximately 5% of the project value was spent on training, which included life skill-, HIV/Aids-, construction health and safety-, and administration-training. Due to the project experience and additional training, the beneficiaries were provided with long-term empowerment, employment and wellness.

In formulating and designing the construction around empowerment, favourable results were obtained. However, certain key social issues were not considered which include evaluating alternative designs through a life cycle assessment to compare construction impacts. Furthermore, the impacts of local climate change were not considered, nor

Table 7
Nkqubela construction and upgrading of baseline Social Sustainable score (Categories rearranged).

Category	Performative social sustainability measures	Score*	Grouping weight	Final score
*To what extent do you agree with the following statements (1 = strongly disagree; 5 = strongly agree) If the project had not considered the performative measure, a score of '0' is awarded.				
Pollution	A life cycle assessment had been conducted and reduction of Emissions, Energy use and Water contamination had been achieved.	0	4.29	0
Pollution	Efforts have been made to reduce Noise during construction and use phases.	3	0.85	2.55
Climate change	The predicted impacts of local Climate Change had been considered and vulnerable pavement systems (including local communities) had been identified. Pavement Resilience had been increased and pavement construction and maintenance impacts on local communities decreased.	0	1.74	0
Socio-economic Impact	The project achieved Fundamental Economic Transformation through, inter alia, providing Educational opportunities for, and seeking the Empowerment of, Targeted Beneficiaries ensuring long-lasting Jobs.	5	3.15	15.75
Local economic development	The project had achieved Local Economic Development through Community Participation, preferential procurement, training, contractor mentorship, etc.	5	1.71	8.55
Safety	Full compliance with Construction Health and Safety Regulations, Road Safety Audit or similar road user's safety assessment.	5	2.26	11.3
Functional Performance	The project ensures an improvement in Stable Flow with a reduction in Travel Time evidenced by a traffic study.	4	2.3	9.2
Functional Performance	Due consideration had been given to Pedestrian Facilities for Safety and Accessibility.	5	1.83	9.15
Functional Performance	Traveller Information Systems are provided during construction and use phases.	3	0.95	2.85
Financial Performance	The project ensured good Value for Money, evidenced by a cost analysis showing an acceptable cost premium against process deliverables.	5	0.92	4.6
SS_s **Total (100)**				**63.95**

is there evidence of attention to additional traveller information systems (including safety notices) or reducing construction and use phase noise. These are some of the key shortcomings identified in the EmpIA which are considered in the S-LCI proposed in this study.

In evaluating the case study, the project is scored against the proposed impact categories shown in Table 5, initially only considering the indicators used in the EmpIA. This score is referred to as the baseline SS_s. The project is then reevaluated implementing additional sustainable evaluations not considered in the EmpIA but listed in the S-LCI of this study. Table 7 summarises the baseline SS_s for the case study.

For the LCA and climate change impact categories, a score of zero was awarded as these measures were not considered and the project receives a total SS_s of 63.95 points and a 'Silver' level of sustainability. By considering the predicted local climate change impacts and settlement vulnerabilities, as well as conducting a life cycle assessment [8], sustainability may be greatly enhanced. It has been shown that an alternative pavement design can save between 25–56% on emissions, 56% on energy use and 58% on water use in South Africa. The water savings may be equivalent to the water requirements for 2,000 people for one week per kilometer pavement constructed [8]. Combined with the predicted climate change impacts of medium to high risk of heat stress, droughts, very hot days and flooding [102], the life cycle savings may greatly assist in reducing these impacts and vulnerabilities. Furthermore, an alternative design may not only present environmental and social savings but commonly also economic savings. An opportunity then exists to utilise the economic savings to provide further training (e.g. sponsoring a local beneficiary for tertiary education).

In re-evaluating the case study applying these additional sustainable evaluations, the alternative approach may be scored using the impact categories proposed in Table 5. A final SS_s of 94.1 points is achieved with a sustainability level 'Evergreen'. This final SS_s illustrates the importance of considering a broad range of social sustainable interventions to ensure long-term performance of the pavement and its impacts on society.

Discussion of results

It is important to note that the EmpIA [93] only focuses on social sustainability from an empowerment perspective. The EmpIA works well to quantify the increased premium on social investment but does not consider the justification of this increased premium on life cycle benefits, assuming that long-term positive economic impacts will be achieved.

The model proposed in this study is qualitatively based but may be applied quantitatively by assessing the premium on the initial investment of the increased process deliverables (e.g. conducting an LCA) and comparing the cost premium of design and process choices (e.g. labour intensive method specifications, training, contract participation goals for local participation, etc.) to alternative options where the increased deliverables are not considered. It is well understood that the increased process deliverables are accompanied by an increased initial investment [77]. However, there is usually a long-term return on investment which may be quantified using standardised methods. It is proposed that an LCCA be used where the premium on initial investment is discounted and compared to economic growth and other economic metrics to assess the sustainability of options.

Even though both models aim to maximise social impacts of pavements, the model proposed in this study considers a broader scope of social sustainability compared to the EmpIA and better considers current challenges (e.g. climate change) and common practices (e.g. LCAs).

Findings and critical shortcomings

Throughout literature, various frameworks are available to measure the sustainability of pavement infrastructure provision, focusing on certain aspects of sustainability such as economic (i.e. LCCAs), environmental (i.e. LCAs) or certain social themes (i.e. EmpIAs), with SRTs being the only standardised framework considering a broader range of sustainability, even though SRTs are typically environmentally dominated. As S-LCAs have recently been introduced to fill the gaps required for confident assessments, standardisation of S-LCA frameworks is not yet available. In attempts at standardisation, many researchers propose diverse and fragmented S-LCA approaches [48], overlooking core issues preventing the consolidation of information. Furthermore, many researchers simply derive indicators from literature without a deeper elaboration of the rationale behind the selection of certain indicators [3,50,14,91]. Attention is typically given to indicators which are most commonly used among data sets, neglecting those that might not have made it past the selection process but may be important. These indicators are often proposed for general use in a broad range of industries and sectors with few receiving sufficient empirical attention to draw reasonable conclusions [48,55,75]. This is extended by the lack of consideration of location-specific evaluations [7], disregarding regional challenges and goals [9]. Moreover, implementing identified indicators may be tedious when practitioners are presented with a long list of indicators as compared to the alternative approach of focusing on the key indicators which contribute significantly to social sustainability. A crucial shortcoming is found where S-LCAs are developed for a certain life cycle phase or more commonly, a 'cradle-to-gate' approach, neglecting use- and end of life-phases. This shortcoming also leads to a general lack of risk consideration, which as detailed in this study, may significantly impact on social sustainability. Risk evaluation is of particular importance when socio-economic impacts are assessed and the long-term return on investment of non-monetary costs are evaluated. Furthermore, gaps in S-LCA subcategories are equally identified where researchers increasingly integrate subjective experiences and perceptions (such as stakeholder satisfaction) into social performance measurements [48], which is virtually absent in the UNEP and SETAC guidelines [5]. In the implementation of S-LCAs, a shortcoming is observed in the approaches of both researchers and industry, where proposed S-LCA frameworks are applied without refining the frameworks to the organisation's specific responsibilities and sustainable objectives, making execution fractured and incoherent [54,79,91].

Conclusions and recommendations

Following a general tendency of literature, most of the studies on sustainability entailing a life cycle perspective focused on fundamental themes recognised as crucial to be protected, i.e. health and safety, natural environment and resources, economic- and functional-performance of pavements related to both motorised and non-motorised road users. These themes have been applied individually and in concert among the various frameworks detailed. However, as concluded by Reitinger et al. [70], 'we are faced with the paradoxical situation of avoiding harm to the environment and human health while ignoring other aspects of human life and thus the aims of sustainability', highlighting the complex relationships that exist among the three tenets of sustainability. It is, therefore, suggested that S-LCAs should complement existing frameworks by focusing on a broader range of social consequences, including social well-being and various socio-economic impacts. A method to achieve this objective is to consider direct effects to stakeholders across the three tenets detailed by a wide range of indicators measuring the quality of life of people on both an individual and collective level [22]. Standardisation of S-LCA frameworks and universal acceptance of social indicators could present road authorities and engineers with relevant information to better understand the important social factors during technical and managerial choices in pavement infrastructure provision.

This research has attempted to achieve this objective by identifying key socially relevant sustainability indicators related to the development and management of pavement infrastructure, using South Africa as a case study. Potential indicators were sourced from a large database consisting of several renowned international inventories and focus was given to the indicators most aligned with social sustainability. Indicators were assessed and scored using an adapted methodology and refinement was conducted through sensitivity analyses using Bayesian-based Monte Carlo simulations to reduce uncertainty. By allowing weightings and scores of sub-goals and criteria to be changed, the results reflect the importance that inputs from local stakeholders have on the impacts of sustainability. This further demonstrates that the methodology adopted in this paper meets the sustainable principle of context and location specificity.

Through literature, certain risks (e.g. fundamental economic transformation) have also been identified which may have validity for consideration when the identified key social indicators are applied to real projects. The typical limitations of similar social impact models, such as spatial dependence and omittance of key indicators not well understood, have been addressed in this study. The model proposed is spatially relevant to South Africa, but can easily be adapted for application in other countries or locales. Furthermore, all key social indicators, regardless of the difficulty in quantification, have been considered and included in the results with a focus on their impacts as opposed to being outcome-based. A worked example is provided which delineates the design and managerial steps which ensure high performance of social sustainability.

Recommendations

As S-LCA standardisation is the main aim of researchers among the literature reviewed, recommendations provided in this study seek to address the shortcomings that need to be considered during standardisation. For future research, there is a need to develop S-LCA frameworks to specific industries and locations rather than detailing a blanket approach for social sustainable assessments. The frameworks should aim to provide industries and specific organisations with key information that needs to be absorbed, refined, and aligned with their specific sustainable objectives to allow confident and long-lasting application. Through this long-lasting application, attention should also shift to a 'cradle-to-grave' approach and aim to measure the social impacts of a product or service over an extended period, to identify the long-term consequences of current sustainable interventions. This should be supplemented by introducing risk-based approaches where the cause-effect relationships of social sustainability are increasingly enhanced.

Declaration of Competing Interest

None

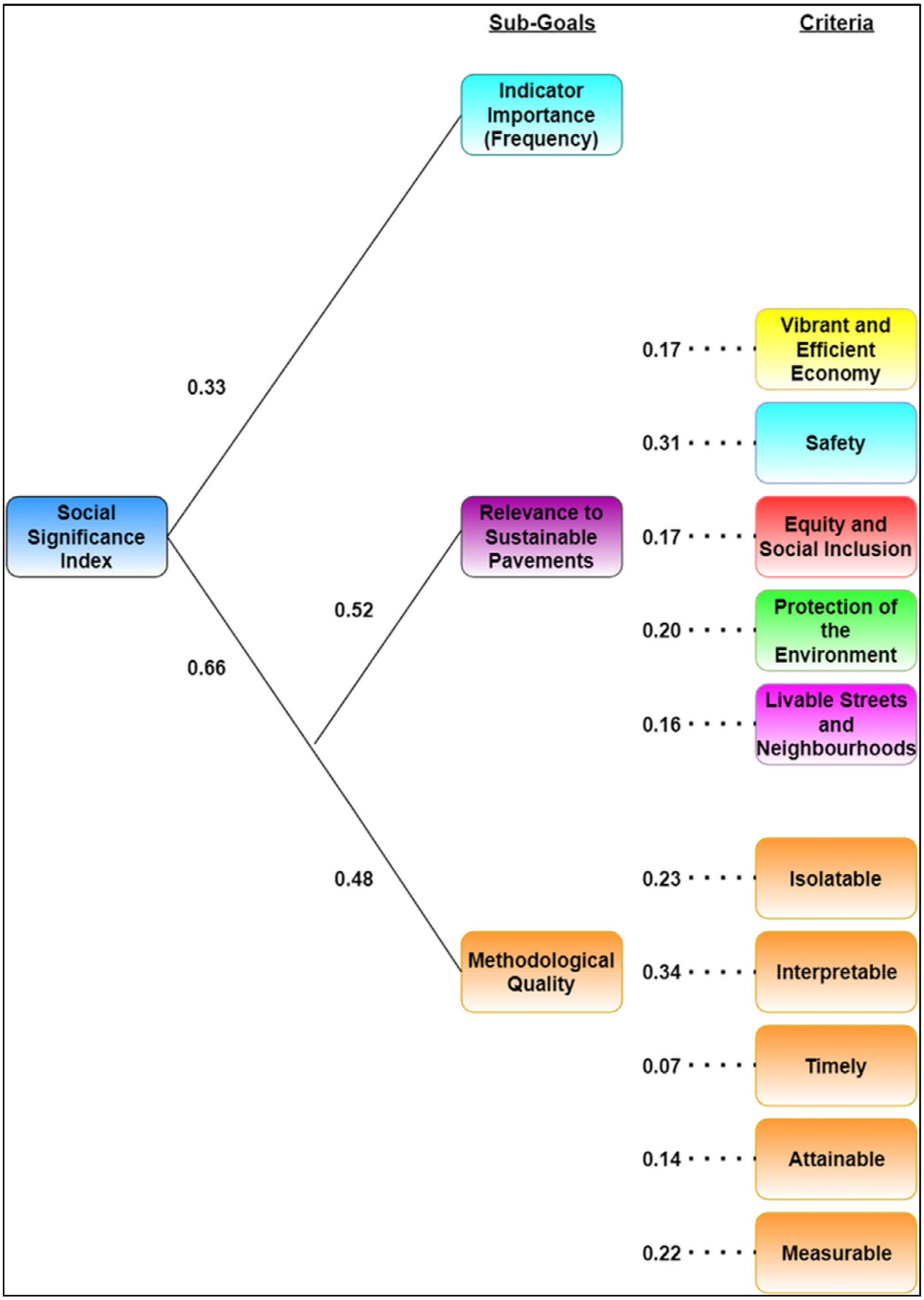
Appendix A. Sustainable transport indicator database for South Africa

Source	Number of Indicators
The Sustainable Development Goals [86]	244
SuRF Rating Tool (SANRAL)	10
Greenroads [29]	61
GreenLITES [60]	175
INVEST [38]	33
I-LAST [37]	153
ENVISION [39]	64
BE^{2}ST-IN-HIGHWAYS [72]	9
OECD Environmental Indicators [61]	64
Developing indicators for sustainable and livable transport planning [53]	41
Framework for measuring sustainable regional development [46]	38
Alberta GPI Blueprint [65]	32
Sustainable Transportation Performance Indicators [27]	14
European Environment Agency core set of indicators [21]	206
Indicators of Airport Sustainability [87]	10
STARS Community Index [80]	83
Sustainability Assessment Indicators [43]	30
Broad Based Black Economic Empowerment [4]	7
WCDTPW EmpIA [93]	5
CSIR – SIA [18]	22
Vanclay [90]	18
Burdge Indicators [11]	26
Cement Sustainability Initiative [17]	7
Total number of Indicators	**1,352**

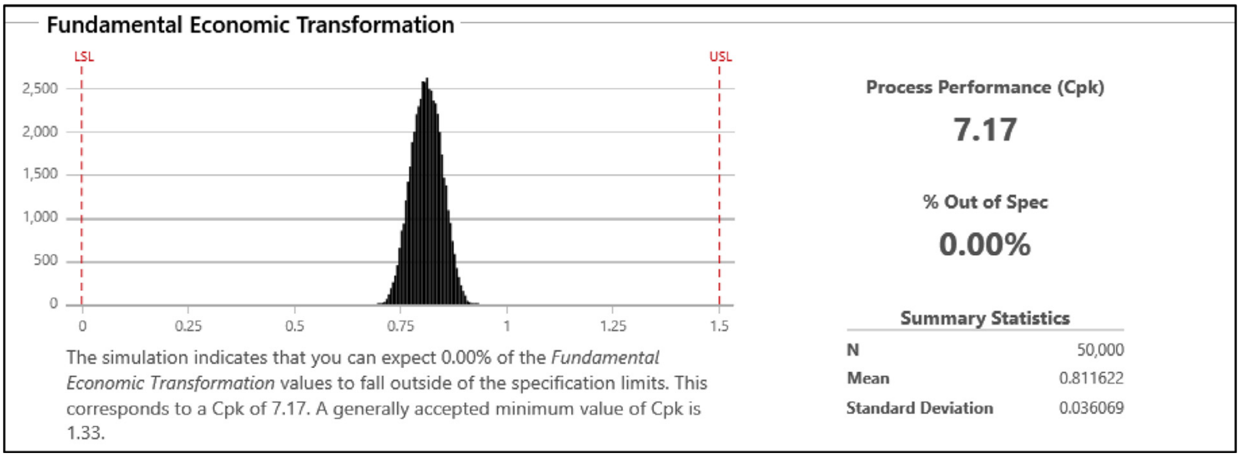
Appendix B. Criteria scoring matrix

	Score				
Criteria	**1**	**2**	**3**	**4**	**5**
Measurability	No measuring technique available	Measuring techniques available but not recognised	Measuring technique available but results need additional processing to confidently use	Well known measuring technique producing variable results	Well known measuring technique producing accurate results
Attainable	Results are unobtainable	Results require development of a model to obtain	Results require application of existing models and input of variables to obtain	Results are obtainable but require some additional processing	Results immediately obtainable
Timely	Results are unobtainable	Results take over a month to obtain	Results may take up to a month to obtain	Results may take up to a week to obtain	Results immediately obtainable
Interpretability	Results are uninterpretable	No consensus exists to interpret results	Confusion exists in interpretation of results	Results are interpretable within reasonable variation of definitions	Results easily interpreted
Isolatibility	Results cannot be isolated	No consensus exists to isolate results	Confusion exists in isolating results	Results isolatable within reasonable variation of definitions	Results easily isolatable

Appendix C. Adapted tree diagram for sub-goal and criterion [13]



Appendix D. Typical results from the Monte Carlo simulations



Fundamental Economic Transformation

The simulation indicates that you can expect 0.00% of the *Fundamental Economic Transformation* values to fall outside of the specification limits. This corresponds to a Cpk of 7.17. A generally accepted minimum value of Cpk is 1.33.

Process Performance (Cpk)

7.17

% Out of Spec

0.00%

Summary Statistics

N	50,000
Mean	0.811622
Standard Deviation	0.036069

References

[1] W.M. Adams, The future of sustainability: re-thinking environment and development in the twenty-first century, Proceedings of the Report of the International Union for Conversation of Nature Renowned Thinkers Meeting, 2006.

[2] A. Anthony, The use of e-procurement in South African publican procurement law: challenges and prospects, Law, Democr. Dev. 22 (1) (2018) 39–47, doi:10.4314/ldd.v22i1.4.

[3] S. Aparcana, S. Salhofer, Development of a social impact assessment methodology for recycling systems in low-income countries, Int. J. Life Cycle Assess. 18 (5) (2013) 1106–1115, doi:10.1007/s11367-013-0546-8.

[4] B-BBEE Act, 2013. Broad-based Black Economic Empowerment Act, No. 46 of 2013. Republic of South Africa, Government Gazette. Cape Town, South Africa. Available online: https://www.gov.za/sites/default/files/gcis_document/201409/37271act46of2013.pdf (Accessed on 20 June, 2020).

[5] C. Benoît, B. Mazijn, UNEP and SETAC. United Nations Environment Programme and Society of Environmental Toxicology and Chemistry. Guidelines for Social Life Cycle Assessment of Products, United Nations Environment Programme, Nairobi, Kenya, 2009 ISBN: 978-92-807-3021-0.

[6] C. Benoît-Norris, D.A. Cavan, G. Norris, Identifying social impacts in product supply chains: overview and application of the social hotspot database, Sustainability 4 (12) (2012) 1946–1965, doi:10.3390/su4091946.

[7] U. Berardi, Clarifying the new interpretations of the concept of sustainable building, Sustain. Cities Soc. 8 (2013) 72–78, doi:10.1016/j.scs.2013.01.008.

[8] S.A. Blaauw, J.W. Maina, Life cycle inventory for pavement – a case study of South Africa, Transp. Eng. J. (2021), doi:10.1016/j.treng.2021.100049.

[9] S.A. Blaauw, J.W. Maina, L.J. Grobler, Life cycle inventory for bitumen in South Africa, Transp. Eng. J. 2 (2020), doi:10.1016/j.treng.2020.100019.

[10] B. Broughton, J. Hampshire, Bridging the Gap: A Guide to Monitoring and Evaluating Development Projects, Australian Council for Overseas Aid, Deakin, Australia, 1997.

[11] R.J. Burdge, The Concepts, Process and Methods of Social Impact Assessment, Social Ecology Press, Wisconsin, USA, 2004 ISBN 0-951042-35-9.

[12] Carte Blanche, 2020. The Construction Mafia. M-Net, The MultiChoice Group, South Africa. Available online: https://www.youtube.com/watch?v=JLlSHWR3SVU&t=133s (Accessed on 20 June, 2020)

[13] H. Castillo, D.E. Pitfield, ELASTIC – a methodological framework for identifying and selecting sustainable transport indicators, Transp. Res. Part D Transp. Environ. 15 (4) (2010) 179–188, doi:10.1016/j.trd.2009.09.002.

[14] T. Corbi'ere-Nicollier, I. Blanc, S. Erkman, Towards a global criteria based framework for the sustainability assessment of bioethanol supply chains, Ecol. Indic. 11 (5) (2011) 1447–1458, doi:10.1016/j.ecolind.2011.03.018.

[15] D. Costa, P. Quinteiro, A.C. Dias, A systematic review of life cycle sustainability assessment: current state, methodological challenges, and implementation issues, Sci. Total Environ. 686 (2019) 774–787, doi:10.1016/j.scitotenv.2019.05.435.

[16] J. Couture, J. Parent, M. Lafontaine, J. Revéret, Lessons learned from integrated environmental and socioeconomic life cycle assessments, in: Proceedings of the 8th International Conference On Life Cycle Assessment In The Agri- Food Sector, Saint-Malo, France, 2012.

[17] CSI, Cement Sustainability Initiative. Getting the numbers right. Cement Industry Energy and CO_2 Performance, World Business Council for Sustainable Development, Geneva, Switzerland, 2016.

[18] CSIR, Council for Scientific And Industrial Research – Social Impact Assessment. Final Environmental Impact Assessment Report For The Proposed Construction, Operation and Decommissioning Of Seawater Reverse Osmosis Plant And Associated Infrastructure in Tongaat, Kwazulu-Natal, Chapter 11: Social Impact, CSIR, Pretoria, South Africa, 2016.

[19] I. Dikmen, M. Birgonul, S. Han, Using fuzzy risk assessment to rate cost overrun risk in international construction projects, Int. J. Proj. Manag. 25 (5) (2007) 494–505, doi:10.1016/j.ijproman.2006.12.002.

[20] T.B. Edil, Building Environmentally And Economically Sustainable Transportation-Infrastructure-Highways. Recycling Materials Resource Center, University of Wisconsin. Madison, USA, 2012 http://rmrc.wisc.edu/wp-content/uploads/2012/09/BEST-for-Colorado.pdf.

[21] EEA, European Environment Agency Core Set of Indicators – Guide, European Environment Agency, Copenhagen, Denmark, 2005 https://www.eea.europa.eu/publications/technical_report_2005_1/file.

[22] P.M. Falcone, E. Imbert, Social life cycle approach as a tool for promoting the market uptake of bio-based products from a consumer perspective, Sustainability 10 (4) (2018), doi:10.3390/su10041031.

[23] FBWP, Free basic water policy. Department of water affairs and forestry, Free Basic Water – Implementation Strategy 2007: Consolidating and Maintaining, Department of Water Affairs and Forestry – Directorate: Policy and Strategy, Pretoria, South Africa, 2007 Available at gov.za.

[24] FHWA, Life Cycle Assessment Of Pavements, Tech Brief. FHWA-HIF-15-001, Federal Highway Administration, Washington, D.C., USA, 2014.

[25] P. Furness, Applications of Monte Carlo simulation in marketing analytics, J. Direct Data Dig. Mark. Pract. 13 (2011) 132–147, doi:10.1057/dddmp.2011.25.

[26] A. Gelman, J. Carlin, H. Stern, D. Rubin, Bayesian Data Analysis, Chapman & Hall, Florida, USA, 1995.

[27] R. Gilbert, N. Irwin, B. Hollingworth, P. Blais, Sustainable Transportation Performance Indicators, Centre for Sustainable Transportation, 2003 http://cst.uwinnipeg.ca.

[28] GreenLITES, Green Leadership in Transportation Environmental Sustainability, New York State Department of transportation, Albany, USA, 2008 https://www.nysdot.gov/programs/greenlites.

[29] Greenroads, The Greenroads Rating System, Greenroads, Redmond, Wash, 2012 Retrieved from http://www.greenroads.org.

[30] K. Griffiths, C. Boyle, T. Henning, Infrastructure sustainability rating tools–how they have developed and what we might expect to see in the future, in: Proceedings of the Institute of Public Works Engineering Australasia. Sustainable Communities Sharing Knowledge, Rotorua, New Zealand, 2015.

[31] J.B. Guinée, Life cycle assessment: Past, present and future, in: Proceedings of the International Symposium on Life Cycle Assessment and Construction. Nantes, France, RILEM Publications, Paris, France, 2012 Keynote Address.

[32] T.M. Gulotta, M. Mistretta, F.G. Practicò, A life cycle scenario analysis of different pavement technologies for urban roads, Sci. Total Environ. 673 (18) (2019) 585–593, doi:10.1016/j.scitotenv.2019.04.046.

[33] HE, Highways England Carbon Tool Guidance, Version 2.1, Highways England, London, UK, 2019.

[34] P.G. Hoel, S.C. Port, C.J. Stone, in: Introduction to Statistical Theory, Houghton Mifflin, New York, USA, 1971, pp. 36–42. New York.

[35] D.A.R. Huarachi, C.M. Piekarski, F.N. Puglieri, A.C. De Francisco, Past and future social life cycle assessment: historical evolution and research trends, J. Clean. Prod. 264 (2020), doi:10.1016/j.jclepro.2020.121506.

[36] R. Hunt, W. Franklin, LCA - how it came about, personal reflections on the origin and the development of LCA in the USA, Int. J. Life Cycle Assess. 1 (1) (1996) Ecomed Publishers. Landsberg, Germany.

[37] IDOT, I-Last - Illinois Livable and Sustainable Transportation Rating System and Guide, Illinois Department of Transportation, 2010 Retrieved from http://www.dot. state.il.us/green/documents/I-LASTGuidebook.pdf.

[38] INVEST, Infrastructure Voluntary Evaluation Sustainability Tool. User Guide, Federal Highway Administration, Washington, D.C., USA, 2012 www.sustainablehighways.org/files/3429.pdf.

[39] ISI, Envision, Sustainable Infrastructure Framework, Version 3, Institute for Sustainable Infrastructure, Washington D.C., USA, 2018.

[40] ISO, ISO 14040, Environmental Management – Life cycle assessment – Principles and Framework, ISO, Geneva, Switzerland, 2006.

[41] A. Janjic, M.S. Stankovic, L. Velimirovic, Multi-criteria influence diagrams – a tool for the sequential group risk assessment, Granular Computing and Decision-Making, Studies in Big Data 10, Springer International Publishing, Switzerland, 2015, doi:10.1007/978-3-319-16829-6_7.

[42] A. Jeffery, BEE: Helping or Hurting?, Tafelberg, Pretoria, South Africa, 2014 ISBN 062407160X, 9780624071600.

[43] C. Jeon, A. Amekudzi, R. Guensler, Sustainability Assessment At The Transportation Planning Level: Performance Measures And Indexes, Transportation Research Board, Washington, D.C., USA, 2008 annual meeting.

[44] R. Johansson, Evaluation of experiences from using CEEQUAL in infrastructure projects: a case study of the Crossrail programme and the Olympic Park Master's thesis, Uppsala University, Uppsala, Sweden, 2011.

[45] G.J. Jordaan, Optimisation of Flexible Road Pavement Rehabilitation Investigations And Design, University of Pretoria, Pretoria, South Africa, 2013 www.lulu.com ISBN 978-1-77592-036-6.

[46] K. Kirk, J. Tableporter, A. Senn, J. Day, J. Cao, Y. Fan, C. Schively Slotterback, E. Goetz, L. McGinnis, Framework For Measuring Sustainable Regional Development For The Twin Cities Region, Center for Transportation Studies, Minnesota, USA, 2010 University of Minnesota Center for Urban & Regional Affairs and http://hdl.handle.net/11299/97673 .

[47] J.F. Knott, J.M. Jacobs, J.E. Sias, P. Kirshen, E.V. Dave, A framework for introducing climate-change adaptation in pavement management, Sustainability 16 (2019) 11, doi:10.3390/su11164382.

[48] M. Kühnen, R. Hahn, Indicators in Social Life Cycle Assessment: A Review of Frameworks, Theories, and Empirical Experience, J. Ind. Ecol. 21 (6) (2017) 1547–1565, doi:10.1111/jiec.12663.

[49] LEED, Leadership in Energy and Environmental Design. LEED for Neighbourhood Development Rating System, U.S. Green Building Council, Washington, D.C., USA, 2010.

[50] A. Lehmann, D. Russi, A. Bala, M. Finkbeiner, P. Fullana-i- Palmer, Integration of social aspects in decision support, based on life cycle thinking, Sustainability 3 (12) (2011) 562–577, doi:10.3390/su3040562.

[51] Y.H. Lin, C.C. Lin, Y.Y. Tyan, An integrated quantitative risk analysis method for major construction accidents using fuzzy concepts and influence diagrams, J. Mar. Sci. Technol. 19 (44) (2011) 383–391.

[52] J. Ling, Z. Du, H. Du, A performance prediction model for airport pavement based on Bayesian analysis of random effects, Int. J. Pavements Conf. (2) (2013) 142.

[53] T. Litman, Well Measured: Developing Indicators for Sustainable And Livable Transport Planning, Victoria Transport Policy Institute, Victoria, Canada, 2019.

[54] V. Mani, R. Agrawal, V. Sharma, Social sustainability in the supply chain: analysis of enablers, Manag. Res. Rev. 38 (9) (2015) 1016–1042, doi:10.1108/MRR-02-2014-0037.

[55] S. Matos, J. Hall, Integrating sustainable development in the supply chain: the case of life cycle assessment in oil and gas and agricultural biotechnology, J. Oper. Manag. 25 (6) (2007) 1083–1102, doi:10.1016/j.jom.2007.01.013.

[56] A. McGoey-Smith, A. Poschmann, L. Campbell, Quantitative risk assessment and risk management of a large transportation project, Int. J. Eng. Res. Technol. 12 (2) (2010) 132–143.

[57] S.T. Muench, J.L. Anderson, M. Söderlund, Greenroads: a sustainability performance metric for roadways, J Gr. Build. 5 (2) (2010) 114–128.

[58] NDP, South Africa National Development Plan 2030, Government of South Africa, Pretoria, South Africa., 2012 Available at gov.za.

[59] I. Nicaise, Social Impact Assessment – Peer Review in Social Protection And Social Inclusion. Synthesis Report. Slovak Republic, European Commission DG Employment, Social Affairs and Equal Opportunities, 2008 Brussels, Belgium.

[60] NYSDOT, NYSDOT Sustainability and GreenLITES – Growing GreenLITES, NYSDOT, New York, USA, 2012.

[61] OECD, OECD Environmental Indicators: Towards Sustainable Development, Organization of Economic Coordination And Development, OECD, Paris, France, 2001 www.oecd.org.

[62] N.C. Onat, M. Kucukvar, O. Tatari, Uncertainty-embedded dynamic life cycle sustainability assessment framework: an ex-ante perspective on the impacts of alternative vehicle options, Energy 112 (1) (2016) 715–728, doi:10.1016/j.energy.2016.06.129.

[63] O.O. Otobo, Risk Management System To Guide Building Construction Projects In Developing Countries: A case study of Nigeria, University of Wolverhampton, Wolverhampton, England, 2016 Doctor of Philosophy thesis.

[64] S. Park, S. Kim, A strategy Bayesian model to predict profit of construction projects, Archit. Res. 13 (3) (2011) 49–56, doi:10.5659/AIKAR.2011.13.3.49.

[65] Pembina Institute, Alberta GPI blueprint report., Pembina Institute, 2001 Alberta, Canada. Available at pemba.org.

[66] PPPFA, 2011. Preferential Procurement Policy Framework Act, No. 5 of 2000. Republic of South Africa, Government Gazette. Cape Town, South Africa. Available online: https://www.gov.za/sites/default/files/gcis_document/201409/a5-000.pdf (Accessed on 20 June, 2020)

[67] PPR, 2017. Preferential Procurement Policy Framework Act, 2000: Preferential Procurement Regulations, 2017. No. R. 32. Republic of South Africa, National Treasury, Government Gazette No. 40553. Cape Town, South Africa. Available online: https://www.gov.za/sites/default/files/gcis_document/201701/40553rg10684gon32.pdf (Accessed on 20 June, 2020)

[68] W.H. Press, S.A. Teukolsky, W.T. Vetterling, B.P. Flannery, Numerical recipes in C: The art of scientific computing. Second Edition, Cambridge University Press, Cambridge, USA, 1992.

[69] P.K.S. Ramirez, L. Petti, N.T. Haberland, C.M.L. Ugaya, Subcategory assessment method for social life cycle assessment. Part 1: methodological framework, Int. J. Life Cycle Assess. 19 (2014) 1515–1523, doi:10.1007/s11367-014-0761-y.

[70] Reitinger, C.; Dumke, M.; Barosevcic, M.; Hillerbrand, R. A conceptual framework for impact assessment within SLCA. Int. J. Life Cycle Assess. Volume 16, pp. 380–388. 10.1007/s11367-011-0265-y

[71] RICS, Royal Institute of Chartered Surveyors. Life cycle costing, 1st Edition, RICS, London, UK, 2016 ISBN 978-1-78321-136-4.

[72] RMRC, 2012. Recycled Materials Resource Centre. BE^{2}ST-in-Highways^{TM}: BE^{2}ST-in-Highways^{TM} at RMAUPG Annual Meeting. Available online: http://rmrc.wisc.edu/be2st-in-highways/ (Accessed on 20 June, 2020)

[73] I.R. Sarsam, Sustainable and green roadway rating system, Int. J. Sci. Res. Environ. Sci. 3 (3) (2015) 99–106, doi:10.3390/su12218884.

[74] Y. Sato, K. Miyamoto, K. Kitazume, Quantitative risk analysis of road projects based on empirical data in Japan, J. East. Asia Soc. Transport. Stud. (6) (2005) 3971–3984.

[75] S. Seuring, J. Koplin, T. Behrens, U. Schneidewind, Sustainability assessment in the German detergent industry: from stakeholder involvement to sustainability indicators, Sustain. Dev. 11 (4) (2003) 199–212, doi:10.1002/sd.216.

[76] Y.L. Shen, W.C. George, S.K. Catherine, Risk assessment for construction joint ventures in China, J. Constr. Eng. Manag. 127 (1) (2001) 10.1061/(ASCE)0733-9364(2001)127:1(76).

[77] SIPDM, Standards for Infrastructure Procurement and Delivery Management, National Treasury, South Africa, 2016 Available at treasury.gov.za.

[78] SONA, 2020. State of the Nation Address. President Cyril Ramaphosa, African National Congress, Government of the Republic of South Africa. Pretoria, South Africa. Available online: https://www.gov.za/speeches/president-cyril-ramaphosa-2020-state-nation-address-13-feb-2020-0000 (Accessed on 20 June, 2020)

[79] L.J. Spence, L. Rinaldi, Governmentality in accounting and accountability: a case study of embedding sustainability in a supply chain, Account. Organiz. Soc. 39 (6) (2014) 433–452, doi:10.1016/j.aos.2012.03.003.

[80] The Sustainability Tracking, Assessment & Rating System (STARS), 2020. The Association for the Advancement of Sustainability in Higher Education (AASHE), USA. Available online: https://stars.aashe.org/about-stars/ (Accessed on 20 June, 2020)

[81] WJvdm. Steyn, P. Paige-Green, Evaluation of issues around road materials for sustainable transport, in: Proceedings of the 28th Southern African Transport Conference, Pretoria, South Africa, 2009 ISBN 978-1-920017-39-2.

[82] B. Sundeep, A Decision Making Approach for Selection of Sustainable Pavements in texas by Integrating Life Cycle Cost Analysis (LCCA), Life Cycle Assessment (LCA) of Environmental and Social Impacts, The University of Texas at El Paso, 2016.

[83] O. Swei, J. Gregory, R. Kirchain, Probabilistic characterization of uncertain inputs in the life-cycle cost analysis of pavements, Transport. Res. Rec. 2366 (2013) 71e77, doi:10.3141/2366-09.

[84] M. Tymošenk, K. Golovach, Modelling of the prospects for sustainable development of agricultural territories by the Bayesian networks, Manag. Theory Stud. Rural Bus. Infrastruct. Dev. 40 (2) (2018) 263–273.

[85] UCPRC, Pavement Life Cycle Assessment Workshop: Discussion Summary And Guidelines. UCPRC-TM-2010-03, University of California Pavement Research Centre, Davis, California, USA, 2010.

[86] UN, United Nations: The Sustainable Development Goals Report 2019, United Nations, New York, USA, 2019.

[87] P.J. Upham, J.N. Mills, Environmental and Operational Sustainability Of Airports: Core Indicators And Stakeholder Communication, Tyndall Centre for Climate Change Research, UMIST. Manchester, UK, 2003.

[88] T.J. Van Dam, J.T. Harvey, S.T. Muench, K.D. Smith, M.B. Snyder, I.L. Al-Qadi, H. Ozer, J. Meijer, P.V. Ram, J.R. Roesler, A. Kendall, Towards Sustainable Pavement Systems: A Reference Document, US Department of Transportation Federal Highway Administration, 2015 FHWA-HIF-15-002Washington, D.C., USA.

[89] D. van Ravenzwaaij, P. Cassey, S.D. Brown, A simple introduction to Markov Chain Monte–Carlo sampling, Psychon. Bull. Rev. 25 (2018) 143–154, doi:10.3758/s13423-016-1015-8.

[90] F. Vanclay, International principles for social impact assessment, Impact Assess. Proj. Apprais. 21 (1) (2003) 5–11 Available at from: http://www.iaia.org/publicdocuments/special-publications/SP2.pdf.

[91] M. Varsei, C. Soosay, B. Fahimnia, J. Sarkis, Framing sustainability performance of supply chains with multidimensional indicators, Supply Chain Manag. Int. J. 19 (2) (2014) 242–257, doi:10.1108/SCM-12-2013-0436.

[92] Z. Wang, Probabilistic Modelling Of Flexible Pavement Overlay Performance And Performance-Related Pay Adjustment, State University of New Jersey, New Jersey, USA, 2016 Doctor of Philosophy. Rutgers.

[93] WCDTPW, 2010. Western Cape Department for Transportation and Public Works. Empowerment Impact Assessment Guideline. Expanded Public Works Programme. Empowerment Impact Assessment Unit, Department for Transport and Public Works, Provincial Government Western Cape. Western Cape, South Africa. Available online: https://www.westerncape.gov.za/assets/departments/transport-public-works/Documents/revised_empowerment_impact_assessment_guideline.pdf (Accessed on 20 June 2020)

[94] WHO, World Health Organisation. Air Quality Guidelines Global Update: Particulate Matter, Ozone, Nitrogen Dioxide And Sulphur Dioxide, WHO, Copenhagen, Denmark, 2005 EUR/05/5046029.

[95] World Bank, Value for Money: Achieving VfM in Investment Projects Financed By The World Bank, World Bank, Washington D.C., USA, 2016 www.worldbank.org.

[96] D. Wu, C. Yuan, H. Liu, A risk-based optimisation for pavement preventative maintenance with probabilistic LCCA: a Chinese case, Int. J. Pavement Eng. 18 (1) (2017) 11–15, doi:10.1080/10298436.2015.1030743.

[97] J.a.M.T.A. Yudelson, The Green Building Revolution., Second Edition, Island Press, Washington D.C., USA, 2008 ISBN: 9781597267632.

[98] A. Zamagni, H.L. Pesonen, T. Swarr, From LCA to life cycle sustainability assessment: concept, practice and future directions, Int. J. Life Cycle Assess. 18 (2013) 1637e1641 doi.org/10.1007/s11367-013-0648-3.

[99] Y. Zhang, J.P. Mohsen, A project-based sustainability rating tool for pavement maintenance, Engineering 4 (2) (2018) 200–208, doi:10.1016/j.eng.2018.03.001.

[100] X. Zheng, S.E. Easa, T. Ji, Z. Jiang, Incorporating uncertainty into life-cycle sustainability assessment of pavement alternatives, J. Clean. Prod. 264 (2020), doi:10.1016/j.jclepro.2020.121466.

[101] J. Zietsman, H. Khreis, It's complicated: transportation's relationship with public health, Tex. Transp. Res. 55 (2) (2019) 12–13.

[102] F Engelbrecht, A Le Roux, K Arnold, J Malherbe, Green Book. Detailed projections of future climate change over South Africa, Council for Scientific and Industrial Research, Pretoria, South Africa, 2019 In presshttps://pta-gis-2-web1.csir.co.za/.