# A Cumulative Risk and Sustainability Index for Pavements

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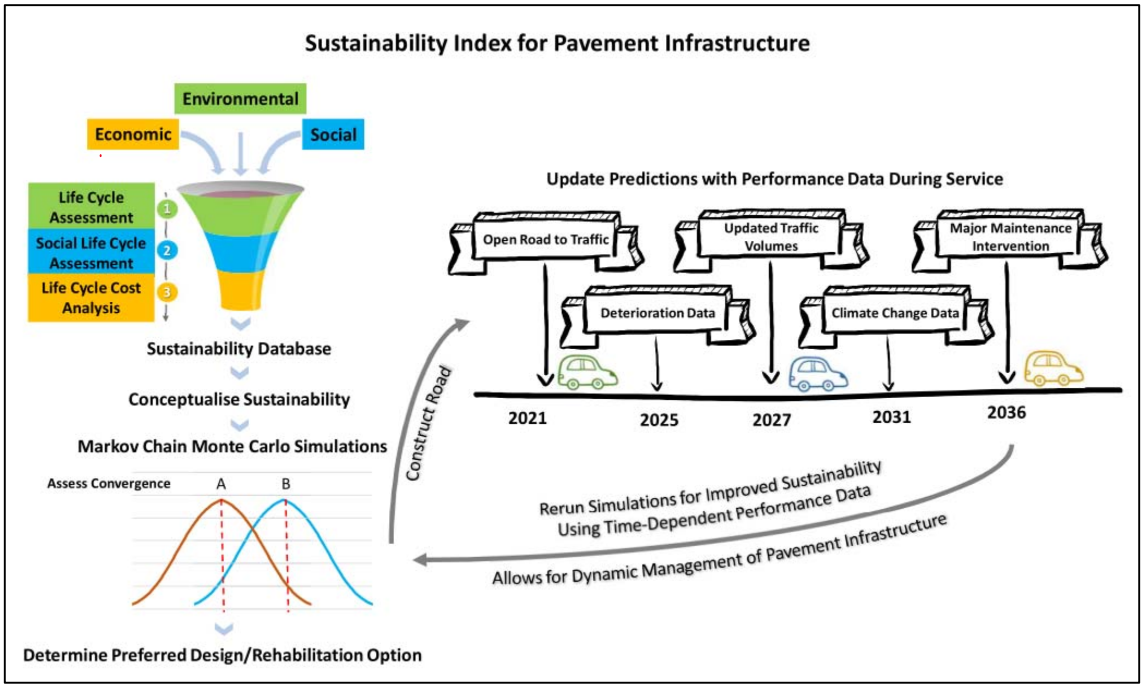
## Graphical Abstract



## Abstract

Pavement sustainability is measured using various methodologies which often focus on only certain aspects of sustainability. Methods to quantify and unify holistic sustainability in terms of economic, environmental and social consequences are lacking. In previous papers, the major findings of the contribution of construction, maintenance and use to pavement sustainability were presented. The objective of this paper is to present a method of quantification using a sustainability index that can compare the design and maintenance options of pavement systems. The model utilises Markov Chain Monte Carlo simulations applied to a conceptualised influence diagram to determine the probability of sustainability using a cumulative approach. Previously reported results are provided which form the basis of the model, detailing economic, environmental and social results of pavement alternatives, followed by the development of a probability model to quantify holistic pavement sustainability. In conclusion, even though sustainability is complex, simplification through simulation is achievable.

**Keywords:**

Life cycle approach, cumulative risk, sustainability index, Markov Chain Monte Carlo.

## 1 Introduction

A sustainable pavement has to be economically, socially and environmentally feasible and viable at an acceptable level of risk over its design life. Practically, a sustainable pavement optimises a range of performance indicators including cost, functionality, safety, local economic and human development, job creation, carbon emissions, climate change, and natural resource use, measured using a suite of assessment methodologies.

The fast pace of development of these methodologies has arguably left gaps in research (Santero et al., 2011; Harvey et al., 2014). Most notably, consideration of risks that may affect sustainability have largely been overlooked. Sustainability is a multifaceted concept where it is often difficult to modify one risk factor without affecting another (Nisbet et al., 2001). Furthermore, changes to or addition of risks, if not properly considered, may cause significant and unanticipated reductions in sustainability outcomes; highlighting the need for a model where risks and their relation to sustainability are properly defined. When risk management related to the construction industry is evaluated, research often focuses on the construction phase, specifically on risks that affect construction time, cost, and quality (Zou and Zhang, 2009; Shen et al., 2001; Chen et al., 2004), omitting other risk categories such as social risks, environmental risks, climate-change risks and governance risks.

A significant constraint is that risks affecting sustainability, which cover a broad scope, are not easily identified and their impacts are often ambiguous. One approach which may be used to simplify the multiplex relationship of these risks is to apply an influence diagram methodology often used to conceptualise complicated neural networks where a variety of inputs, pathways, ‘nodes’, and outputs are modelled. An influence diagram may then be used to support a cumulative risk assessment approach. This approach has been successfully applied to specific case studies regarding pavements (Rossouw et al., 1997; Knott et al., 2019), and is the approach recommended by both the US Environmental Protection Agency (US EPA, 2003) and the South African Department for Environmental Affairs and Tourism (Kotze, 2004). However, a limitation to cumulative risk assessments is to track risks over temporal scales, excluding crucial impacts such as climate change or the observed performance of a pavement over its life cycle. They are also typically developed for planning and design phases without an option for extending their use for management purposes (i.e. being a dynamic model).

A statistical technique, Markov-Chain Monte Carlo (MCMC) simulations, may be used to circumvent this limitation. The MCMC simulation models the probability of the subsequent event on the state attained in the previous event and may allow for a time-step evaluation of the evolution of risk of a pavement over its design life, incorporating constantly changing risks emanating from, for instance, climate change and its effects on pavement deterioration. The MCMCs are further useful as they may simulate the probability of sustainability, providing an index score (i.e. sustainability index) to evaluate alternative designs. The probability modelling provides an additional metric for road authorities to manage the sustainability of their pavements and readily identify whether additional interventions are required and what those interventions should focus on (i.e. maintenance, climate change resilience, etc.).

The objective of this paper is to present a method of holistic pavement sustainability quantification and a practical sustainability index. The MCMC model is used to quantify holistic pavement sustainability on a time-step basis. Background of the study and previously reported results are provided. This is followed by defining risk and sustainability within a pavement context and reviewing important indicators which predominantly affect sustainability. Finally, conclusions and recommendations around the impacts of certain risks on sustainability are provided.

## 2 Structure of the study

This paper proposes a framework for the development of a risk and sustainability index based on a weighted cumulative approach, aiming to extend current research and capable of incorporating novel risks that may arise from impacts such as climate change. The paper structure is illustrated in Figure 1, and detailed as follows:

1. First, the context and system description of the paper is presented where relevant data from previous studies, representing the sustainable database for this study, are reproduced.
2. Second, risk and sustainability within the context of pavement engineering are defined. These definitions are essential for confident assessment and detailing the system boundaries of the study.
3. Third, the probabilistic model is developed through evaluating existing methods and limitations. This is followed by conceptualising sustainability using an influence diagram where the relationship between the sustainable indicators are defined as the basis of the probabilistic model. The key objective of conceptualisation is to unify the three tenets of sustainability.
4. Fourth, MCMC techniques are applied to the conceptualisation used to determine the sustainability index and risk of pavement alternatives.
5. Fifth, discussions and critical shortcomings are provided, together with guidance for reproduction of the results presented in this paper and followed by the conclusions.

Sustainable database development from previous studies.

Conceptualise sustainability as basis of model

Findings of the study are synthesized and discussed with critical shortcomings in extant literature detailed. Guidance for future research is provided.

Defining risk and sustainability within context of pavement engineering.

Applying Markov-Chain Monte Carlo simulations to evaluated conceptualised sustainability model to determine the sustainable index of pavement alternatives.

**Figure 1: Research Structure**

## 3 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. Various risks are associated with achieving sustainable objectives which have not yet been holistically defined in road projects and have been handled in a disjointed manner to date, precipitating the need for a risk approach to the sustainable provision of pavement infrastructure.

These risks are underpinned by a general inability to confidently measure the three pillars of sustainability, with only the economic tenet having mature methodologies available. To address the environmental impacts, Blaauw and Maina (2021) developed the first South African life cycle inventory for typical pavement materials and construction activities, allowing quantification of construction, maintenance and demolition. This was followed by the development of a social life cycle inventory quantifying the principal social impacts of pavement infrastructure provision (Blaauw et al., 2021). Finally, a complete life cycle assessment was conducted inclusive of road user emissions incorporating climate change impacts and related pavement deterioration trends (Blaauw et al., 2022). The main results of the pavement performance incorporating climate change impacts are reproduced in Figure 2, showing the deterioration of a typical strong pavement structure for two different maintenance strategies. The deterioration results are predominantly dependent on traffic levels and the analysis period utilised. For the results shown in Figure 2, the traffic loading is 10 300 annual average daily traffic with 3% truck traffic and a total loading of 10 million equivalent standard axles. The analysis period is 30 years. It is noted that traffic volume and pavement design are linked, and in Blaauw et al. (2022), a matrix of low/high traffic volumes and weak/strong pavements were used to demonstrate the influence of climate on different road categories.

Figure 3 shows the corresponding operating speeds, where the correlation with pavement deterioration is evident. Operating speeds were calculated with the World Bank Highway Development and Management 4 (HDM-4) speed prediction model which utilises a calibrated database of vehicle fleets. The database contains vehicle characteristics required for calculating vehicle speeds, operating costs, travel time costs, effect of speed limit and other vehicle effects.

Figure 4 shows the contribution of various life cycle phases to total emissions for the two maintenance regimes. Similarly to the deterioration results shown in Figure 2, life cycle results are also predominantly affected by traffic levels and analysis periods. The results in Figure 4 utilise the same traffic levels and analysis period as the results from Figure 2. Table 1 shows typical economic results for pavement alternatives. Reproduction of all results from previous studies would make this paper unwieldy.

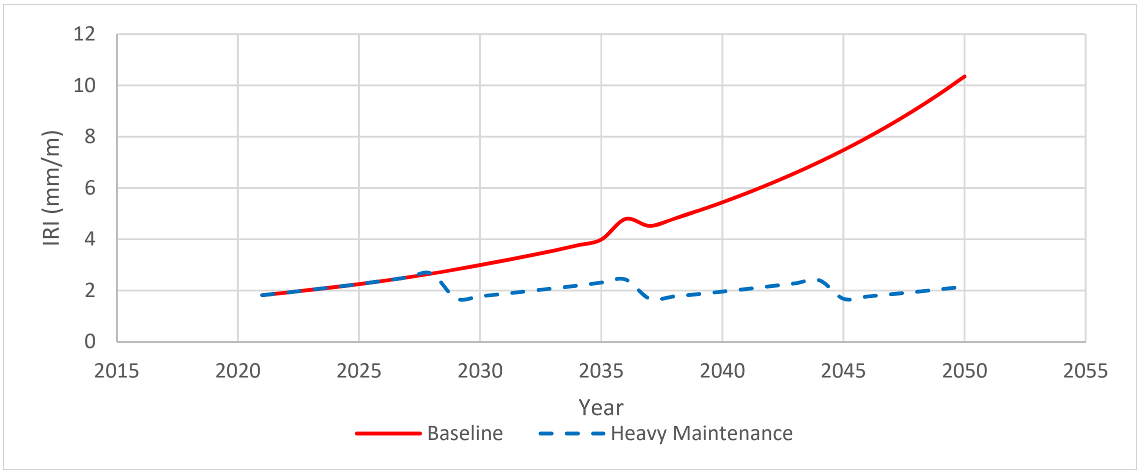


**Figure 2: Pavement deterioration for maintenance alternatives (IRI = International Roughness Index) (Blaauw et al., 2022)**

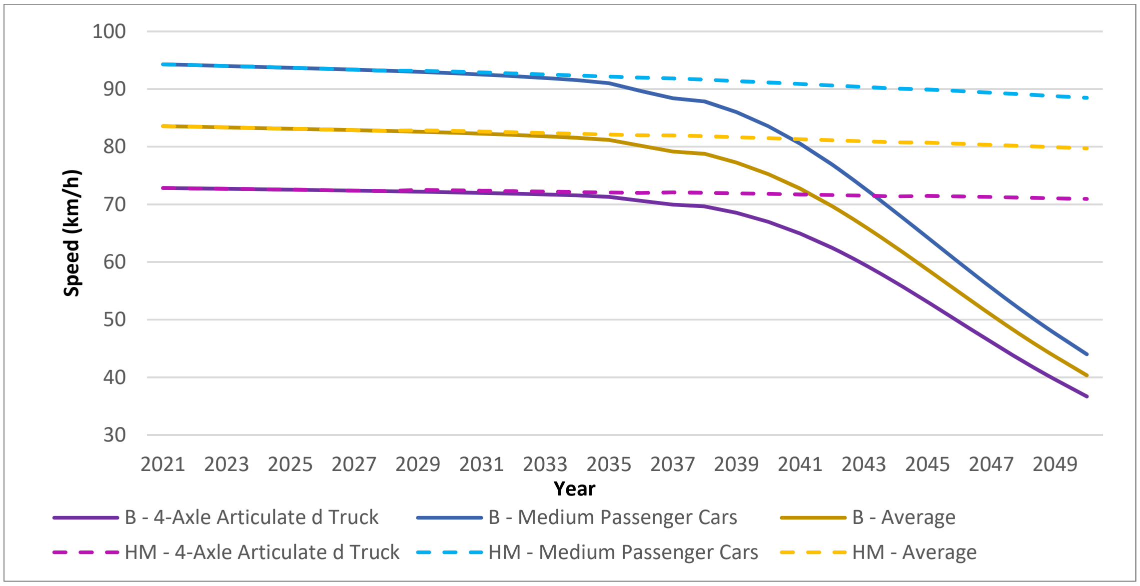


**Figure 3: Operating speeds for maintenance alternatives (B = Baseline, HM = Heavy Maintenance) (Blaauw et al., 2022)**

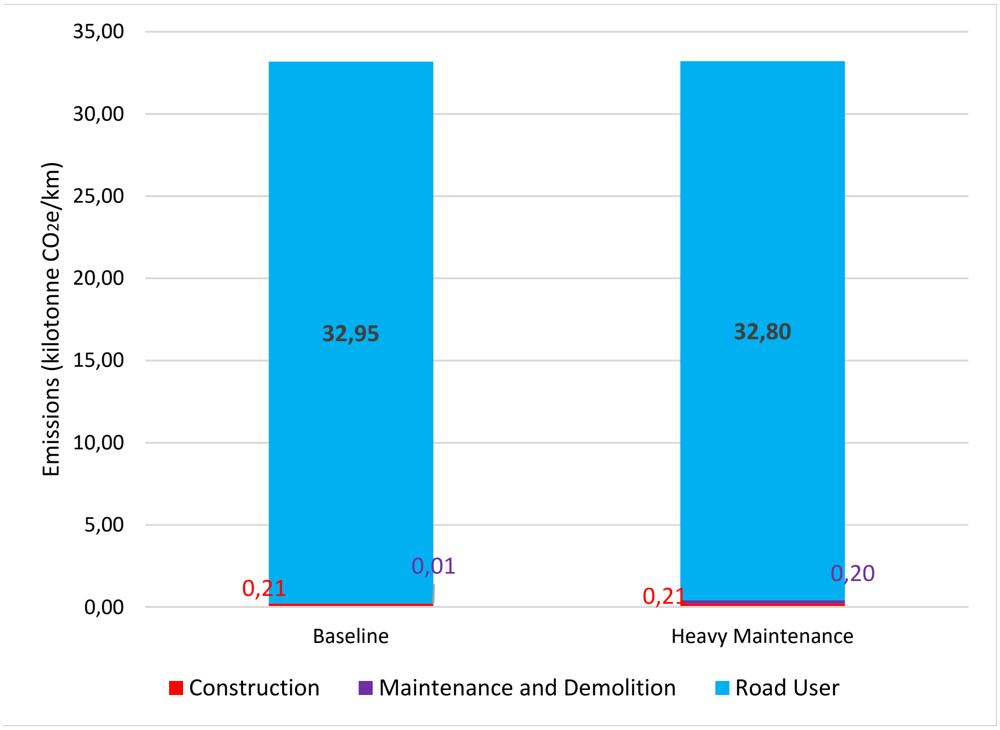


**Figure 4: Life cycle assessment for maintenance alternatives (B = Baseline, HM = Heavy Maintenance) (Blaauw and Maina, 2021; Blaauw et al., 2022)**

**Table 1: Cumulative Discounted Authority Costs for the Baseline, the increase in Heavy Maintenance (HM) cost and the net present value (NPV) per km (costs in million) (Blaauw et al., 2022)**

| Pavement Structure | Maintenance Regime | Rand value (R) |
|---|---|---:|
| **Strong** | **Baseline** | 0.598 |
| | **HM Increase** | 0.937 |
| | **NPV** | 3.49 |
| **Weak** | **Baseline** | 0.600 |
| | **HM Increase** | 0.935 |
| | **NPV** | 6.72 |

These results will be used in this study to both conceptualise and quantify holistic sustainability.

## 4 Defining Risk and Sustainability

Risk and sustainability indexing is a new concept combining traditional risk management practices with the fast-evolving concept of sustainability (WBCSD, 2016). It is a crucial part of any organisation in the construction industry. However, the term risk and its relation to sustainability have often been misused given the lack of a common understanding of what it means. To address this problem, this paper provides a detailed description of both risk and sustainability, as well as their correlation.

### 4.1 Defining Risk

Risk is generally defined as either industry or situationally dependent instead of being universally applicable. Different industries have different definitions of 'risk' and subsequently 'risk management'. ISO 31000 (2018) defines risk as "the effect of uncertainty on objectives," and the risk may refer to positive as well as negative possibilities and the probability distribution of the uncertainty is known. The Organisation for Economic Co-operation and Development (OECD, 2008) defines risk as having positive effects when related to opportunities.

Knightian uncertainty, an ideology from the early 19th century (Knight, 1921) may perhaps be the most famous of risk definitions, stating that risk and uncertainty should be viewed separately: "Uncertainty must be taken in a sense radically distinct from the familiar notion of Risk, from which it has never been properly separated". Many economists in the 1920s and 1930s shared this view, while others argued the distinction is overblown (Dizikes, 2010).

Fischhoff et al. (1984) considered defining risk in a policy setting, stating that its definition is often controversial and that the choice of definition influences the outcome of the policy debates, the allocation of resources among safety measures and the distribution of political power in society. According to ISO Guide 73 (2009) and ISO 55000 (2014), risk is the effect of uncertainty on objectives. In addition, risk can be determined as the product of consequence of failure (CoF) and probability of failure (PoF) of an asset. CoF is the impact of an asset reaching functional failure whereas PoF is the likelihood that an asset will reach functional failure. Furthermore, functional failure of an asset is described as a point in time beyond which the asset fails to fullfil its basic functions at an acceptable level of service. In this study, therefore, the determination of risk is given as a product of the consequence and the probability that sustainable performance will be maintained into the future as shown in Equation 1:

$$\boldsymbol{Risk = Consequence\ of\ Failure\ (CoF)\ \times Probability\ of\ Failure\ (PoF)} \quad \text{(Eq. 1)}$$

### 4.2 Defining sustainability

Berardi (2013) states that when defining sustainability, one must look at the common denominator between definitions in which peculiarities and uncertainties are often encountered (Grosskurth and Rotmans, 2005); where sustainability is defined within multiple dimensions and levels of space (and scale) and is time and socially dependent (Acai and Amadi-Echendu, 2018).

When defining sustainability, Berardi (2013) suggests that spatial dependence should be considered and be regarded as locally specific and a matter of local interpretation rather than being universally applicable. Berardi furthermore states that the local perspective of sustainability will influence the boundaries of sustainable development as the interconnectedness of systems, people and markets tend to counteract a local approach. Sustainable development actions should thus commence from a local scale and develop into the larger global dimension, rather than taking a top-down approach which often disregards location-specific challenges and circumstances. In pavement engineering, this may include considerations such as societal and local climate challenges, materials and analytical design methodologies.

The time dependency, as illustrated in the generational approach of the Brundtland definition (WCED, 1987) and the 15 years for both the Millennium Development Goals (MDGs) and the Sustainable Development Goals (SDGs), requires the long-term consideration of the current actions. This leads to the question of how far into the future should be considered and how much uncertainty can be accepted as a result (Kemp and Martens, 2007). To support the debate of time dependency, Hjorth and Bagheri (2006) argue that linear cause-effect mechanisms are not able to explain the complexities inherent within the issues of sustainability. Hjorth and Bagheri suggest a 'project' should not be considered as having an endpoint but be regarded as an ongoing process part of everyday life, similar to the recently introduced concept of circular economy (WEF, 2014).

Another concept of sustainability, regarding the domain in which it is divided, is based on the categorisation in terms of the three tenets of sustainability, i.e. environmental, economic and social. These dimensions are universally accepted and implemented within the realm of sustainability. However, recent developments have increased the need to recognise cultural and political dimensions (Vallance et al., 2011).

Further uncertainties arise within the multiple interpretations of sustainable development which advance the necessity to consider various points of view and requires acceptance of uncertainty and differences (Berardi, 2013). This is illustrated by Solow (1993) who defines sustainability as preserving production capacity for a long future. Walker and Salt (2012) defines it in terms of resilience and safeguarding the balance between function and structure, observing that sustainability is the capacity of a system to absorb a shock or disturbance and still retain its basic function and structure. The resilience disposition of sustainability echoes the challenge of servicing current system demands without jeopardising the potential to meet those of the future (Acai and Amadi-Echendu, 2018).

Further attempts at defining sustainability have been made by Korczak and Kijewska (2016) who defined sustainability from a transportation perspective, stating that to achieve sustainability, special attention should be given to the degree of satisfaction of individuals who make use of the transport infrastructure and demands governments to clearly define sustainability, taking into account basic human needs when strategic plans and budgets are developed.

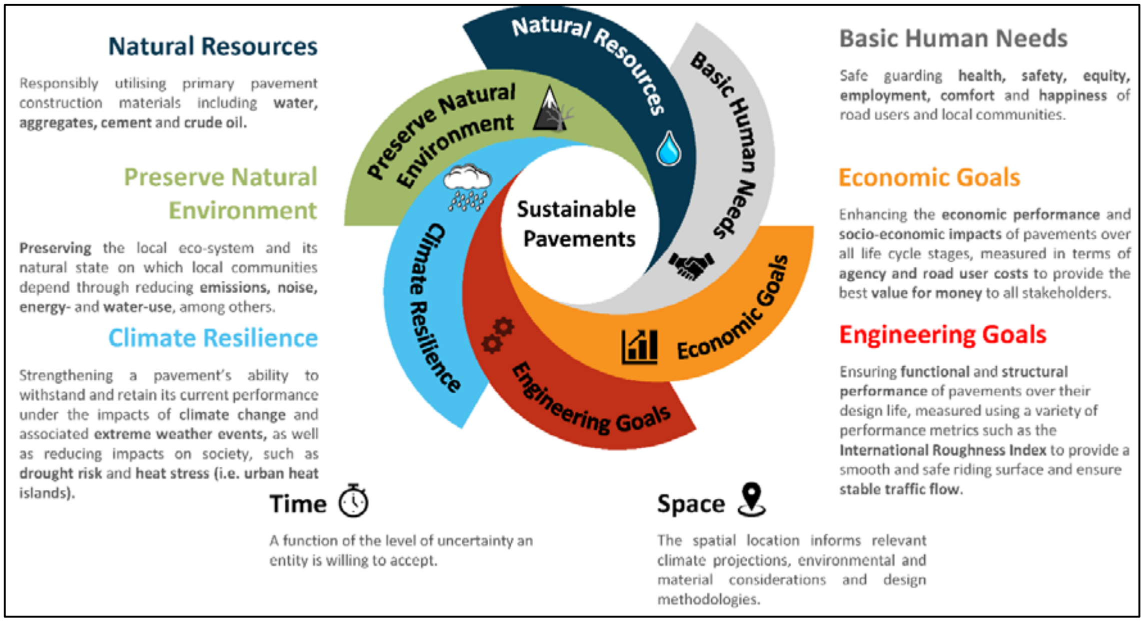
The World Bank (1995) defined biophysical sustainability as the preservation of the integrity of life-supporting systems on earth, with others defining it according to the common definition of preserving the current state (Klauer, 1999). Brundtland's definition focuses on the ability of humans to meet their current needs whereas Schröter et al.'s (2017) definition centres around the conservation of the planetary eco-system.

These definitions show that sustainability requires a pluralistic approach, taking into account multiple factors to create a common definition by minimising trade-offs and the different perceptions of stakeholders. In their concluding remarks, Hjorth and Bagheri (2006) state that even though it is difficult to put sustainable definitions into operational practice, the often single or multi-purpose approach to projects should be changed to a holistic and integrated approach that links the three tenets of sustainability and evaluates the effect of the project on basic human needs.

Applying these considerations to pavements, Van Dam et al. (2015) opine that sustainability should be defined as the system characteristics that encompass a pavement's ability to "achieve the engineering goals for which it was constructed, preserve and (ideally) restore surrounding ecosystems, use financial, human, and environmental resources economically, and meet basic human needs such as health, safety, equity, employment, comfort, and happiness".

The authors propose that this definition include an additional crucial component, 'climate resilience', and may be simplified as follows: the system characteristics that encompass a pavement's ability to meet basic human needs while achieving the economic and engineering goals for which it was constructed, enhancing its climate resilience, preserving and (ideally) restoring the natural environment whilst responsibly consuming natural resources. Details of the basic human needs as well as economic and engineering goals need not be defined at this level as they are project-related. Figure 5 provides a visual illustration of this definition together with key qualification measures emphasised.

It is noted that detailed qualification of the various components of sustainability is provided in later sections, focused on the fundaments of this research. For future research, these qualification measures should be developed either project or authority specific and researchers should not solely rely on the results from this study, but rather use them as guideline.



**Natural Resources**

Responsibly utilising primary pavement construction materials including **water, aggregates, cement** and **crude oil.**

**Preserve Natural Environment**

**Preserving** the local eco-system and its natural state on which local communities depend through reducing **emissions, noise, energy-** and **water-use,** among others.

**Climate Resilience**

Strengthening a pavement's ability to withstand and retain its current performance under the impacts of **climate change** and associated **extreme weather events,** as well as reducing impacts on society, such as **drought risk** and **heat stress (i.e. urban heat islands).**

**Basic Human Needs**

Safe guarding **health, safety, equity, employment, comfort** and **happiness** of road users and local communities.

**Economic Goals**

Enhancing the **economic performance** and **socio-economic impacts** of pavements over all life cycle stages, measured in terms of **agency and road user costs** to provide the best **value for money** to all stakeholders.

**Engineering Goals**

Ensuring **functional** and **structural performance** of pavements over their design life, measured using a variety of performance metrics such as the **International Roughness Index** to provide a smooth and safe riding surface and ensure **stable traffic flow.**

**Time**

A function of the level of uncertainty an entity is willing to accept.

**Space**

The spatial location informs relevant climate projections, environmental and material considerations and design methodologies.

**Figure 5: Defining sustainability related to pavement engineering**

## 5 Markov Chain Monte Carlo Simulations

MCMCs are a statistical method used in probability analyses to obtain information about distributions, used especially for posterior distributions in Bayesian inference (van Ravenzwaaij et al., 2018). A great strength of MCMCs is that they can draw data from a distribution where, for example, the only thing known of the distribution is its density. This is particularly useful in concepts that are difficult to quantify, such as sustainability. The Markov Chain property of MCMC generates samples based on a special sequential process, where each random sample is used as a steppingstone to generate the next random sample – hence the chain, allowing for the incorporation of temporal scales.

These methods have been successfully implemented in the field of pavement risk management (McGoey-Smith et al., 2010; Knott et al., 2019). The study by Knott et al. utilised a hybrid bottom-up/top-down approach to investigate the time dependence of the climate risks which may be used to identify critical effects for intervention planning. The study started by identifying climate stressors through literature and engaging with experts and stakeholders. Secondly, the study identified vulnerable pavement systems, such as coastal roads at risk of sea-level rise and pavements located in regions where there is a high risk of extreme temperature and moisture intense events. Thirdly pavement performance was measured using MnPAVE software where a variety of performance metrics were analysed.

The study concluded by constructing adaptation pathways using a pavement climate sensitivity catalogue, down-scaled climate projections, performance metrics and sustainability indicators. The performance metric was modelled using Monte Carlo simulations and two typical pavement scenarios were modelled:

- HMA thickness required to achieve minimum 85% reliability for < 1 MESA.
- HMA thickness required to achieve a minimum of 90% reliability for > 1 MESA.

The study effectively modelled how HMA overlay thickness and timing, reflective of different maintenance strategies, would affect the performance of a pavement given climate change impacts. The approach by Knott et al. is particularly relevant to the objectives of this study as the developed model in this study includes consideration of climate change impacts, performance metrics, and life cycle assessments for different road scenarios where maintenance strategies are focused on as key determinants for sustainability.

## 6 Limitations of probabilistic methods

The MCMC algorithm is a powerful tool to draw samples from a distribution when all that is known of the distribution is its likelihood. As an example, it is easier to calculate the likelihood of a test score of 50 if the mean population score is 50 compared to if the mean was 100. This theory ‘works’ as long as certain conditions, representing the limitations, are met.

Firstly, the likelihood calculated during the analysis and used to reject or accept the null hypothesis must accurately reflect the distribution function of the proposal in the target distribution. When MCMC is applied to Bayesian inference, the values calculated are required to be from posteriori likelihoods, or at least proportional to the posteriori distribution. Secondly, the proposed distribution should be symmetrical. If the distribution is asymmetric, a modification step is required using, for instance, the ‘Metropolis-Hastings’ algorithm. Thirdly, as the initial estimate of the Markov chain might be very wrong, it should be ignored. If considering a typical Markov chain simulation graphically shown in Figure 6, it is seen that the initial guesses deviate substantially from the final estimate and have likely not been obtained from the target distribution. Only after the first few iterations have been run does convergence occur, and the results may confidently be used. One way to alleviate this problem is to use better starting points. Starting values that are closer to the mode of the posteriori distribution will ensure faster convergence and fewer problems associated therewith (van Ravenzwaaij et al., 2018). It is also noted that convergence is a key indicator to assess the ability of MCMCs to conform to data sets and are often used to validate results.

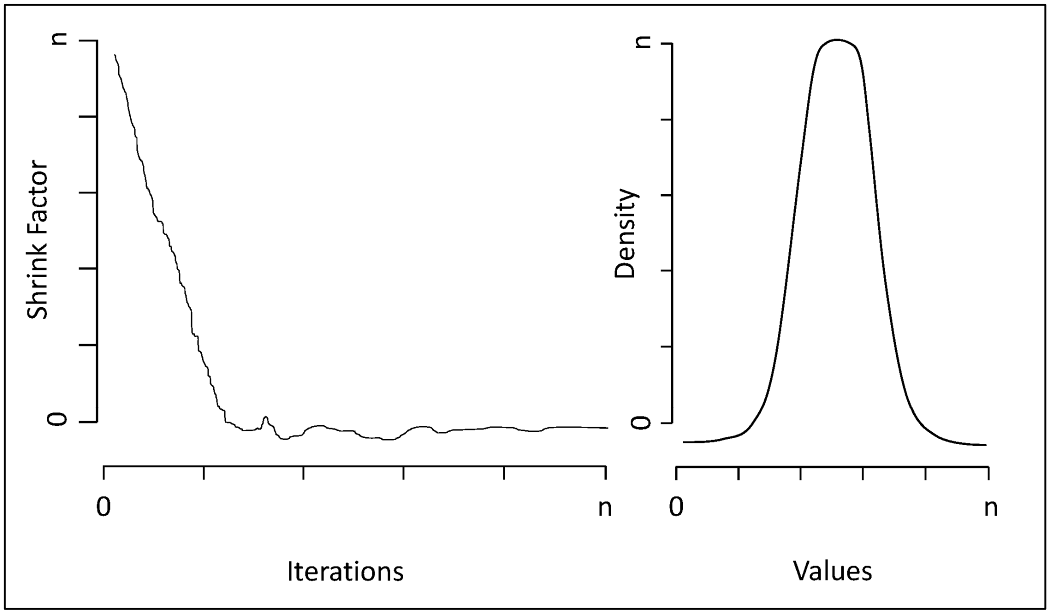


Figure 6: A simple example of MCMC simulation results

## 7 Conceptualising Sustainability

For conceptualising, the identified risk indicators from literature and previous research are categorised and simplified. To achieve this an influence network diagram is employed. Each risk indicator, obtained from Blaauw et al. (2021), is assessed against four main sustainable categories or ‘nodes’, namely: environmental impact, social impact, functional performance and governance. The results of this assessment are shown in Figure 7 and used to develop the MCMC model in subsequent sections.

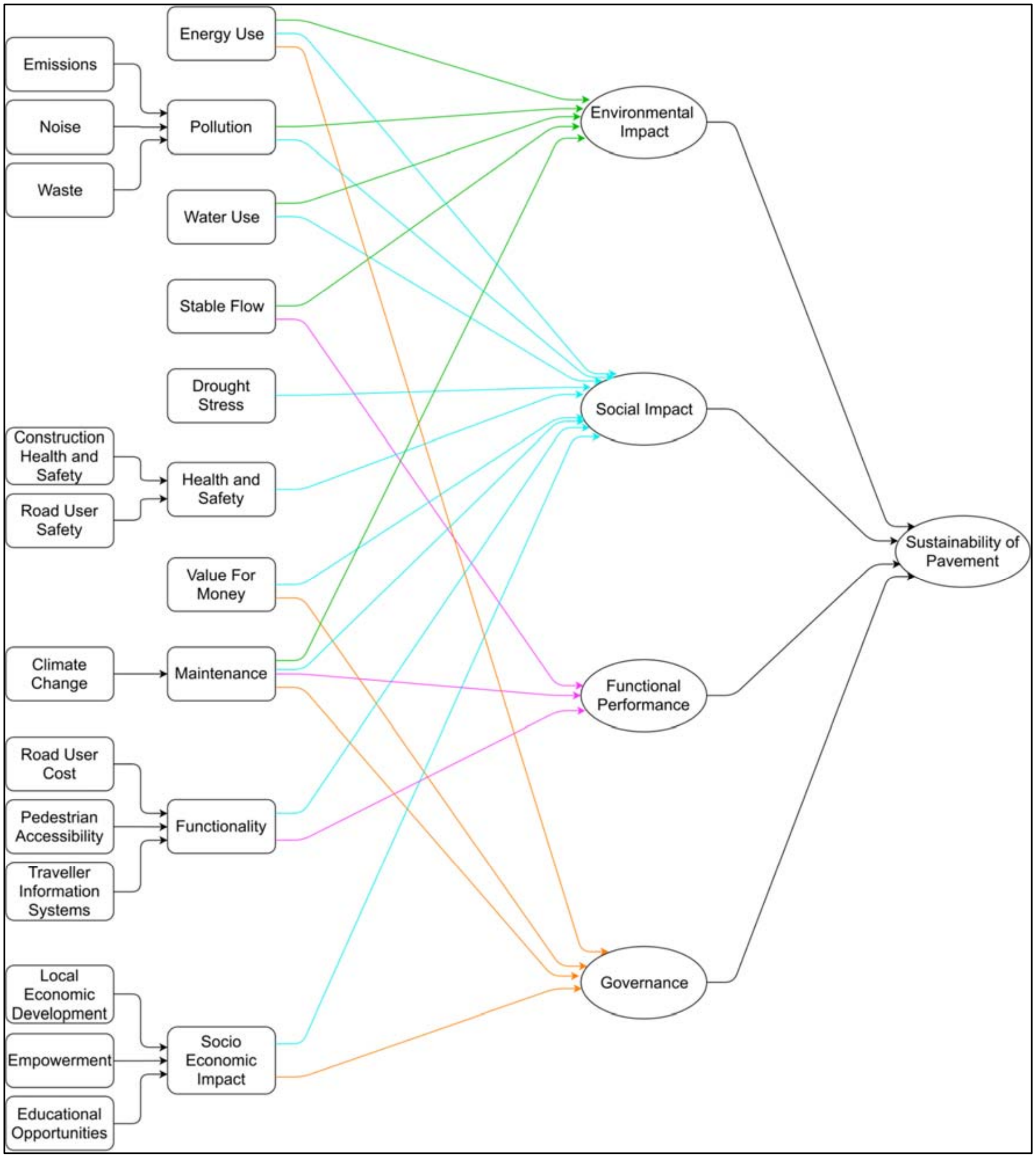


**Figure 7: Influence network diagram of sustainable pavement risk factors (indicators obtained from Blaauw et al. (2021))**

## 7.1 Model description

In developing the MCMC model to be applied to the key risks conceptualised in Figure 7, an approach to align the model with the definition and system boundaries of sustainability provided in Figure 5 is followed. This approach utilises a hybrid bottom-up/top-down strategy to incorporate the temporal and spatial dependence of risks relevant to sustainable pavement infrastructure; allowing for the model to circumvent the common shortcomings of many pavement response models that rely on the linear-elastic theory. These shortcomings manifest as simplified assumptions, that stresses or strains, for instance, are not influenced by histories resulting in often non-hereditary evaluations. Rather, this model considers both past and future risks which collectively influence the sustainability of a pavement over its life cycle.

In simple terms, the model is developed to be dynamic, allowing constant inputs of new data during the pavement management process to not only assess performance against the baseline projections determined during the design phase but to also determine the nature and extent of interventions required in the future to retain a predetermined level of sustainability. Key factors that will influence this performance are climate change and resulting pavement deterioration, true traffic volumes and implemented maintenance actions (Blaauw et al., 2022). Furthermore, settlements that are impacted by the pavement may be monitored for vulnerabilities and the management of the infrastructure may be altered to ensure these vulnerabilities are not further exacerbated, and in an ideal sense, are mitigated. The main settlement vulnerability focused on in this study is drought risk, exacerbated by the use of large volumes of water for construction.

For model development, risks are initially provided equal weights throughout. This contrasts with the common method of assigning different weights to each risk according to its relative impact. The approach was deliberately selected as there is no objective process to determine weights that would apply to all road authorities in South Africa, nor internationally. Rather, the compounding effect of each risk on the four risk categories, shown in Figure 7, is used to reflect the impact of each risk; where, for instance, even though ‘maintenance’ initially has the same weight as ‘drought risk’, the compounding effect of ‘maintenance’ results in four times greater impact on sustainability. This also allows for relative ease in identifying the sensitivity of the model to each risk. It is proposed that road authorities incorporate this model into their pavement management systems and determine the relative weights of each risk individually according to the mandates and sustainable objectives of each authority. Stakeholder engagement and expert interviews may be best suited to determine these weights. Figure 8 provides a visual illustration of the model description.

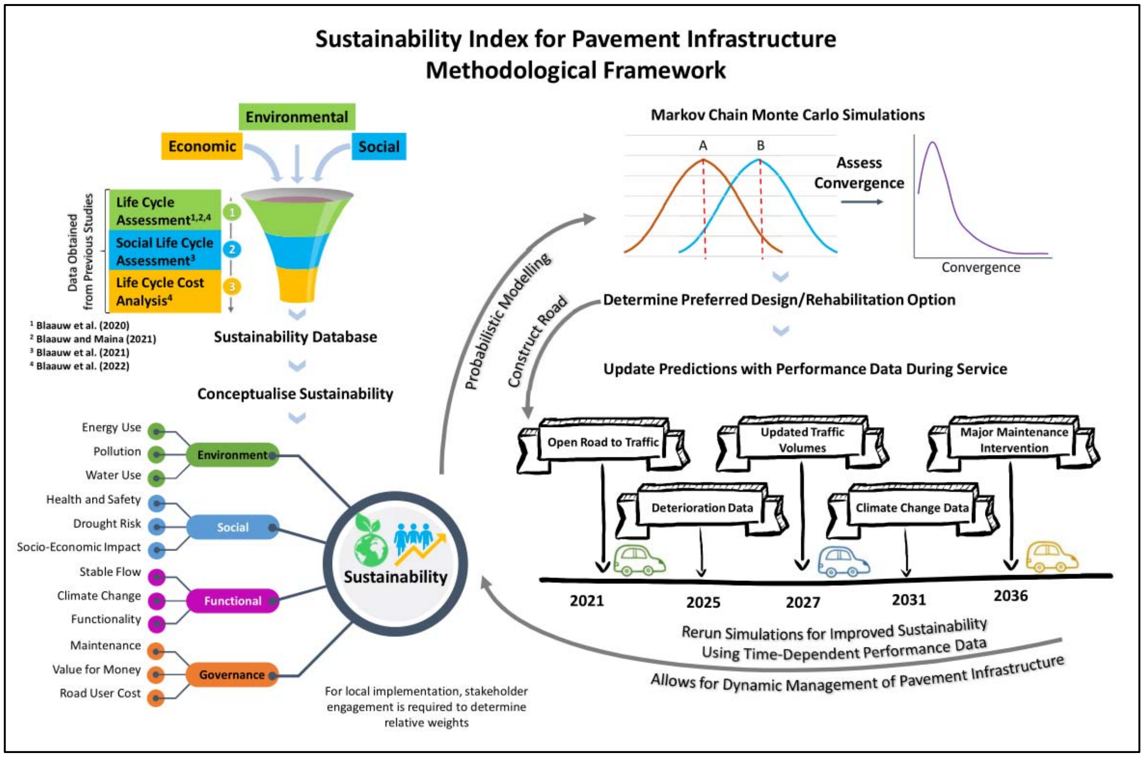


**Figure 8: Model Description for Implementation**

Additionally, the model is developed to be a comparative model during the design phase as the probability of sustainability is modelled amongst alternatives, requiring multiple data sets; meaning a minimum of at least two alternatives is required. After selection of the preferred design, that design is carried forward and may further be modelled on a singular comparative basis incorporating new measured data, as illustrated in Figure 8. The comparison occurs between the new data (i.e. pavement survey data, observed climate change impacts, etc.) and the original design (which acts as the new baseline). This allows for ease in highlighting weaknesses or strengths in the in-service pavement performance and interventions may be more easily identified and implemented.

In using alternative designs, the score of each risk is normalised to a value between 1 and 5 based on the least sustainable alternative, where 1 is the 'worst' achievable score. It is further noted that the development of the model, following the above-described approach, is inevitably bias towards a high probability of sustainability; meaning that alternatives that are likely to result in a low probability of sustainability will generally not conform well to the model and outputs are expected to reflect this, most notably in the ability of simulations to converge.

Convergence, as previously discussed, occurs when the generated Markov Chain distribution converges to the posteriori distribution being modelled and is assessed based on the ability of the distribution to reach stationarity. Convergence is also used to determine the accuracy of the probability predictions and the ability of the model to conform to the data set. A shrink factor is used to monitor whether the simulations have converged to equilibrium. If equilibrium is achieved, the shrink factor will be one. The data sets used in this study consider four possible alternative road scenarios, detailed in subsequent sections. It is noted that cleaning and pre-processing of raw data occur during the various life cycle assessments conducted to develop the 'sustainable database' as illustrated in Figure 8.

### 7.2 Road scenarios

To apply the MCMC model and determine the impacts of an accumulation of risks on the probability of sustainability, four road scenarios, (Blaauw et al., 2022) are utilised. The road scenarios consider two alternative pavement structures (one strong and one weak) and two maintenance regimes (Baseline and Heavy Maintenance), detailed in Table 2.

**Table 2: Pavement structures and maintenance regimes (Blaauw et al., 2022)**

| **Design Traffic** | ES10* |
|---|---|
| **AADT/lane**** | 10 300 |
| **AADTT/lane***** | 300 |
| **Pavement Structure – Strong** | 40 mm continuously graded asphalt on 150 mm G1 and 300 mm C4 on 7% CBR (SNP 4.07) |
| **Pavement Structure - Weak** | 40 mm continuously graded asphalt on 150 mm G2 and 200 mm C4 on 7% CBR (SNP )3.44 |
| **Baseline Maintenance Regime** | Routine maintenance of pothole repair, crack sealing, edge repair and ancillary works |
| **Heavy Maintenance Regime** | Major interventions such as resurfacing or rehabilitation besides routine maintenance |

* 10 million standard axles

** AADT = Annual Average Daily Traffic

*** AADTT = Annual Average Daily Truck Traffic

SNP = Adjusted Structural Number

The base alternative represents a routine maintenance regime of pothole repair, crack sealing, edge repair and ancillary works; whereas the heavy maintenance focuses on major interventions such as resurfacing or rehabilitation besides routine maintenance.

Both pavement build-ups conform to the Category B flexible pavement requirements of SAPEM (2014), with a constructed International Roughness Index (IRI) of 1.6 m/km and a terminal IRI of 4.2 m/km. Additionally, the location of the road is in a subhumid-dry climatic zone, with climate change impacts expected to increase the aridity of the region, accompanied by an increased settlement drought risk.  The four road scenarios are detailed in Table 3.

**Table 3: Road scenarios for modelling**

| Road Scenario | Pavement Structure | Maintenance Regime |
|---|---|---|
| 1 | Weak | Baseline |
| 2 | Weak | Heavy Maintenance |
| 3 | Strong | Baseline |
| 4 | Strong | Heavy Maintenance |

## 7.3 Data Inputs

For each road scenario, quantifiable data inputs are calculated through a variety of methodologies and existing models, such as HDM-4 and previously developed life cycle- and social life cycle-assessment methodologies (Blaauw and Maina, 2021; Blaauw et al., 2021). These data have been calculated for each year over the 30-year analysis period and the performance of the data are indicated predominantly by maintenance interventions over the life cycle which predominantly affect the NPV, user benefits, and road user emissions. For each road scenario, the average value for each indicator and calculated node value shown in Figure 7, are summarised in Table 4.

**Table 4: Average 30-year Data Inputs for Model**

| Indicators | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 |
|---|---|---|---|---|
| Energy Use | 2.67 | 4.12 | 3.04 | 4.16 |
| Pollution | 3.77 | 2.77 | 3.77 | 4.11 |
| Water Use | 3.00 | 3.50 | 4.00 | 3.50 |
| Stable Flow | 1.93 | 3.68 | 2.56 | 4.61 |
| Drought Stress | 3.00 | 3.50 | 4.00 | 3.50 |
| Health and Safety | 3.00 | 5.00 | 3.00 | 5.00 |
| Value for Money | 3.75 | 4.32 | 4.01 | 4.86 |
| Maintenance | 1.00 | 5.00 | 1.00 | 5.00 |
| Functionality | 3.77 | 4.10 | 3.77 | 4.30 |
| Socio-Economic Impact | 4.12 | 4.83 | 4.49 | 5.00 |
| **Nodes** | | | | |
| Environmental Impact | 3.01 | 3.43 | 3.35 | 4.01 |
| Social Impact | 3.27 | 3.76 | 3.70 | 4.05 |
| Functional Performance | 3.07 | 4.08 | 3.08 | 4.08 |
| Governance | 3.50 | 5.00 | 4.00 | 5.00 |

## 8 Sustainability Indexing

Utilising the results from previous studies and road scenarios described, the proposed MCMC model was applied to the four road scenarios using the influence diagram shown in Figure 7, to model the cumulative effects of identified risks on the probability of sustainability. These results are shown in Figure 9 to Figure 12 for scenarios 1 to 4 respectively. On each figure, the convergence is shown on the left and probability distribution on the right.

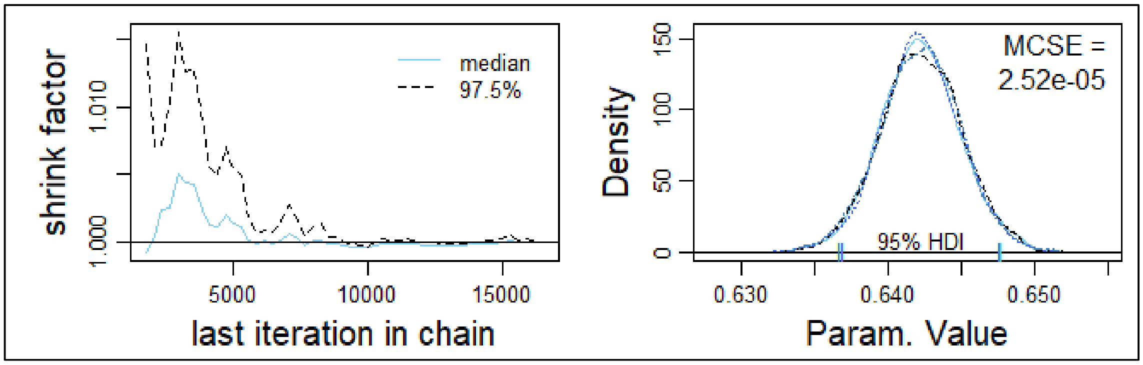


**Figure 9: Scenario 1: convergence (left) and probability of sustainability (right)**

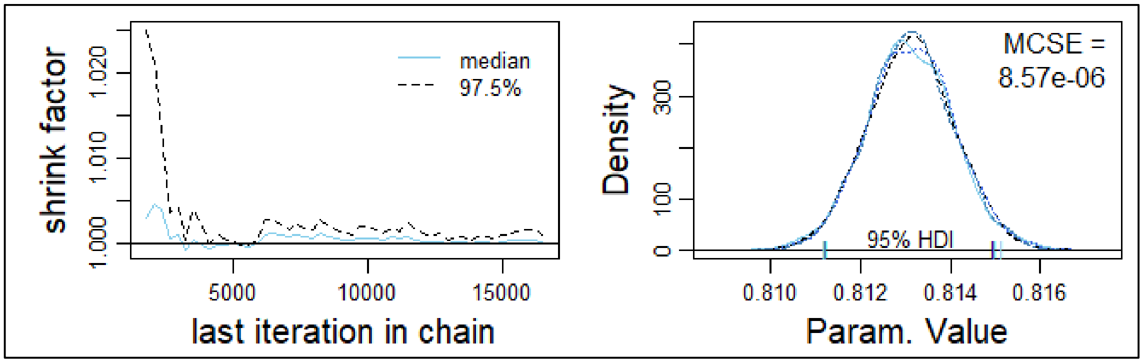


**Figure 10: Scenario 2: convergence (left) and probability of sustainability (right)**

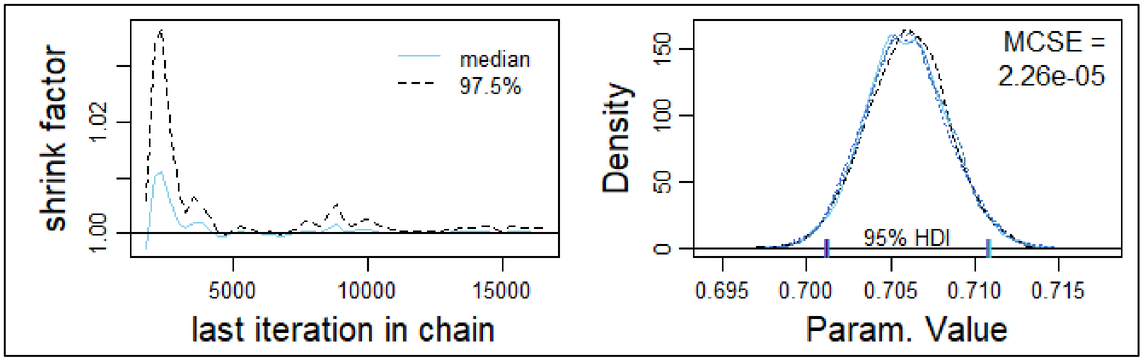


**Figure 11: Scenario 3: convergence (left) and probability of sustainability (right)**

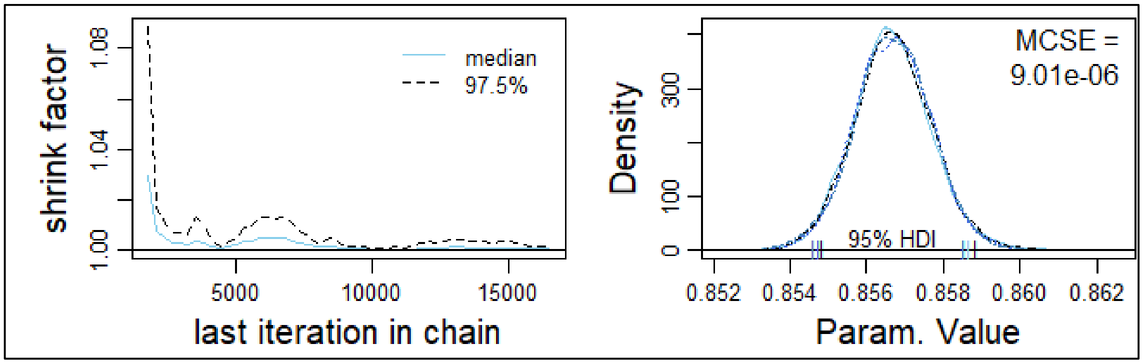


**Figure 12: Scenario 4: convergence (left) and probability of sustainability (right)**

Road scenario 4 has the highest probability of sustainability at 85.67%, followed by scenario 2 (81.31%) and scenario 3 (70.60%). Scenario 1 has the lowest probability of sustainability at 64.23%, summarised in Table 5. It is seen for all simulations that the shrink factor is one, meaning equilibrium has been achieved and a normal distribution is observed throughout.

**Table 5: Sustainability Index of alternatives**

| | **Sustainability Index (*SI*)** |
|---|---|
| **Scenario 1** | 64.23% |
| **Scenario 2** | 81.31% |
| **Scenario 3** | 70.60% |
| **Scenario 4** | 85.67% |

These results may also be viewed as scenario 4 having 14.33% (i.e. 1-85.67%) probability of sustainability failure, compared to scenario 1 with a 35.77% probability of failure. The results are consistent with the life cycle assessment, social life cycle assessment, and climate change assessment results for the same road scenarios. Furthermore, the model converges rapidly for scenario 4 and declines through the scenarios as the probability of sustainability is reduced. This too is expected as the model is inherently biased towards a high probability of sustainability and its inability to conform to the latter scenarios validates their level of unsustainability.

Utilising convergence as a validation criterion in MCMC simulations is a common approach in the industry as convergence is a strong indicator that a model has conformed to a specific data set. It is understood that models which conform to the data sets have significantly better convergence than those which do not. Following this approach, models are typically developed to conform to a predetermined 'ideal' data set, and then applied to other real-world data sets. Convergence can then be used as a good indicator of how well the studied data set correlated to an 'ideal' data set. For this study, the 'ideal' data set reflects the the most sustainable pavement option providing the best value for money, long-term performance, social consideration and the least environmental impacts with relevant data obtained from previously discussed studies.

Figure 13 provides a visual illustration of the simulations, translated into the sustainability index for each road scenario.

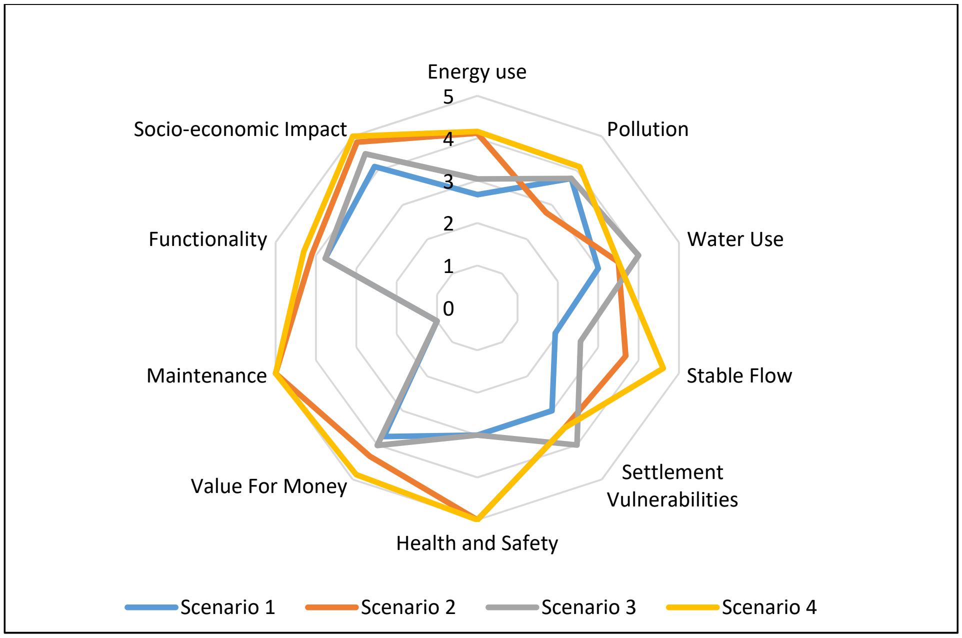


**Figure 13: Sustainability Index for four road scenarios**

## 9 Sustainable Risk

In the previous section, the sustainability index was calculated for various pavement alternatives and reflects the probability of failure, determined by Equation 2:

$$PoF = 1 - SI \qquad \text{(Eq. 2)}$$

where $PoF$ is the probability of failure and $SI$ is the sustainability index shown in Table 5.

Consequences of failure (CoF) in asset management are often a combination of qualitative and quantitative factors and are linked to asset types including maintenance costs, level of service, health and safety, environmental damage, and so forth. In this study four main criticality indices, previously referred to as sustainable nodes, are used: environmental impact, social impact, functional performance and governance. The values for these nodes have been predetermined and are summarised in Table 4. Using these values, the consequence of failure may be determined utilising a simple unweighted index shown in Equation 3:

$$CoF = 5 - \sum_{i}^{n}(node_i \times weight_i) \qquad \text{(Eq. 3)}$$

where $node_i$ refers to the four nodes listed in Table 4 and $weight_i$ equals the importance weighting of each node to sustainability (0.25 used in this study). The importance of each node should be determined by specific road authorities.

It is noteworthy that the aim of this study is comparative and, therefore, a minimum of two designs for the same road are required whereby the sustainability risk is calculated for each relative to each other. The sustainability risk for each alternative is then compared and the preferred option is selected based on the lowest relative risk.

Using Equations 2 and 3, the probability and consequence of failure for each road scenario is calculated, summarised in Table 6 and visually illustrated in Figure 14.

**Table 6: Consequence of Failure for road scenarios**

| | **Probability of Failure ($PoF$)** | **Consequence of Failure ($CoF$)** |
|---|---|---|
| **Scenario 1** | 0.36 | 2.32 |
| **Scenario 2** | 0.19 | 0.81 |
| **Scenario 3** | 0.29 | 1.92 |
| **Scenario 4** | 0.14 | 0.49 |

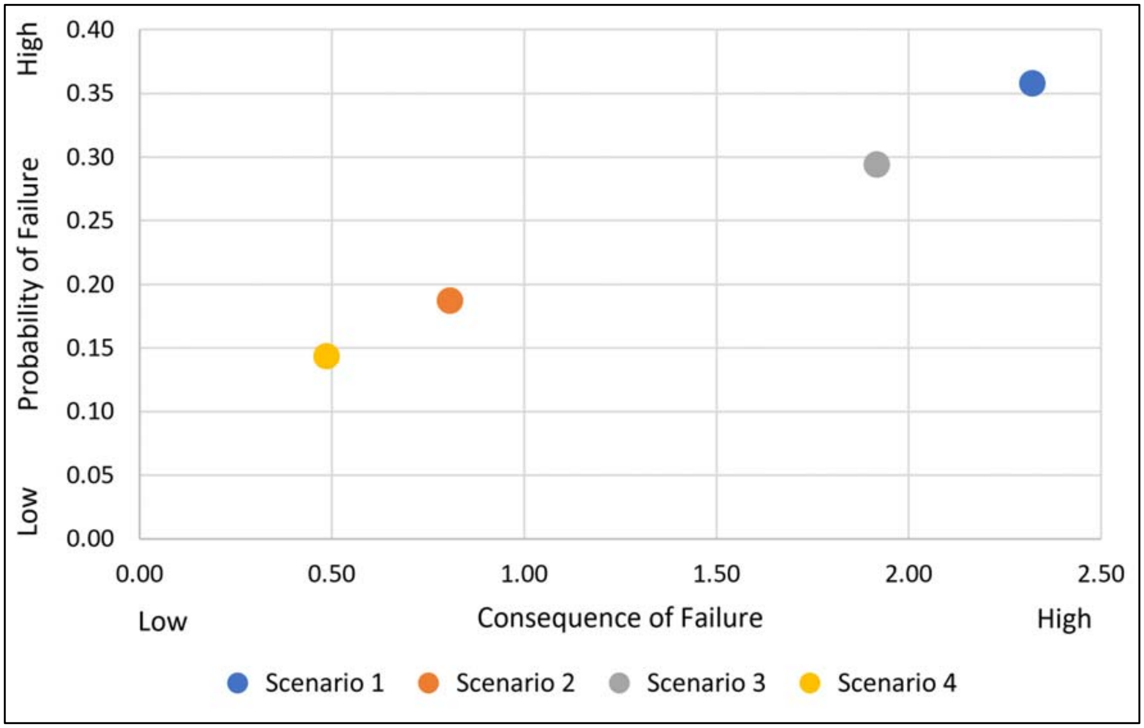


**Figure 14: Sustainability Risk Profile**

From Figure 14 it is seen that the risk profile for each scenario follows a similar trend to the sustainability index results previously presented, with scenario 4 performing best and scenario 1 performing worst. Finally, the sustainable risk may be calculated using Equation 1, summarised in Table 7.

**Table 7: Sustainable Risk for road scenarios**

| | **Sustainable Risk** |
|---|---|
| **Scenario 1** | 0.83 |
| **Scenario 2** | 0.15 |
| **Scenario 3** | 0.56 |
| **Scenario 4** | 0.07 |

From Table 7, it is seen that Scenario 4 has the lowest sustainable risk. Simply put, risk, even though unweighted in this study, reflects the physical risks of environmental damage, climate change, socio-economic impacts, road user benefits, and so forth of a specific road scenario.

Therefore, the selection of Scenario 4 as the preferred design option is expected to provide the most sustainable pavement with the lowest cumulative risk of the infrastructure being unsustainable in the long term.

## 10 Discussion and critical shortcomings

The framework presented in this paper calculates the probability of pavement sustainability over its life cycle given the occurrence of certain risks directly related to sustainability. These risks are categorised as either environmental, social, functional or governance risks which individually and collectively have a cumulative impact on pavement sustainability. The risks were sourced from literature and previous studies on the subject and are either qualitative or quantitative but have a measurable impact on sustainability regardless. ISO 31000 (2018) suggests risk management be an ever-evolving process where risks are continuously identified, assessed, managed, and fed back into the system for improvement. This framework is in line with this suggestion as it is developed for constant monitoring, enhanced intervention planning and improvement for future projects.

The framework in this paper was developed in such a way that it is inherently biased towards a high probability of sustainability and its results are most influenced by ‘maintenance’. Maintenance has commonly been cited as the leading risk in the performance and sustainability of pavements (Steyn and Visser, 2001) in South Africa and internationally (Knott et al., 2019). The findings of this paper support this notion and it is submitted that if sustainable aspirations are to be realised, rigorous proactive maintenance regimes need to be implemented by road authorities, especially in current or future humid climates.

It is noted that the impact of the ‘energy use’ risk has been determined based on current observations in South Africa. However, it is expected that the impact of this risk will significantly increase in the future as the energy market in South Africa continues to degrade and the social impacts of ‘energy use’ become increasingly evident; even more so when the electric vehicle market expands.

Currently, little research exists on cumulative risk assessment in the field of infrastructure development, where existing risk management commonly follows the traditional singular approach. This paper has aimed to provide a basis for incorporating a cumulative approach to risk management for pavements where the probability of sustainability is affected by the collective impacts of a variety of risks. The model was developed to be used by road authorities to not only determine the most sustainable alternative during the design phase but to monitor the preferred design during its in-service life; evaluating both observed performance and additional required interventions if poor performance is detected. This adds an extra metric to be used by road authorities to improve their pavement management systems.

In practice, carbon assessments increasingly accompany economic evaluations of alternative options with little guidance available to determine the preferred solution when the results of the methodologies are in contradiction. It is however understood that the economic tenet typically drives decision making (Practicò et al., 2011). In other sectors, methodologies have been developed to unify the various sustainable tenets (Atai et al., 2020), but current efforts in the field of pavement engineering are lacking. Furthermore, when social consideration is provided, it is limited and often only supplements the other methodologies without fully being utilised in decision making. Thus, in comparison with similar assessment methods such as life cycle assessments or life cycle cost analyses, the value of the model developed in this paper is that not only does it include full consideration of these methodologies, it extends their use far beyond what has typically been achievable. The model unifies the three tenets of sustainability for confident decision making about the impacts a design option will have on the local environment, society and economy. The results of this study further show that when the essence of sustainability is holistically evaluated, optimal outcomes are easily achievable across the three tenets.

A critical shortcoming of current risk assessment frameworks is that they are often unable to measure the direct impact of climate change on pavement performance, and typically adopt a qualitative approach for simplification. The model presented in this paper rather allows for quantifiable assessment of the impacts of climate change on pavement sustainability, by translating high-resolution climate change projections into direct pavement impacts. These impacts include accelerated pavement deterioration which is strongly correlated to increased road user emissions which have been found to account for 99% of the total emissions over a typical pavement life cycle (Blaauw et al, 2022).

## 11 Guidance for future research

For reproduction of the methodology proposed in this study, key guidance notes are provided:

1. Risk and sustainability need to be defined within the context of the project or authority in which the definitions are to be applied;
2. Stakeholder engagement and expert interviews are required to select the key relevant sustainable indicators as well as their relative importance through indicator weighting, and

3. System boundaries need to be clearly defined and should include the functional unit as well as spatial and temporal scales.

Adhering to these simple guidance notes, researchers may develop situationally specific sustainability indices and significantly improve project outcomes.

## 12 Conclusions

The complex nature of sustainability has often resulted in simplification of quantification, focused only on certain sustainability aspects considered to be crucial. These attempts at simplification have further omitted consideration of key sustainability indicators and risks which are difficult to quantify but collectively impact on sustainability, echoing the sentiment of Reitinger et al. (2011), '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'.

In this paper, a method of holistic sustainable pavement quantification and sensible sustainability indexing is presented. A sustainability database is developed from previous studies, with all key indicators and risks considered regardless of the difficulty in quantification. MCMC techniques were applied to the database allowing for time-step modelling of risk over a pavement life cycle, where the start point of modelling can be any time along the life cycle; and both past and future impacts may be modelled collectively. Pavements are living infrastructures that continuously evolve and change and therefore the management tools applied to them should be of a similar dynamic nature, allowing constant inputs of data to monitor and react to any impacts, whether positive or negative.

The model is spatially relevant to South Africa but easily adapted for application in any locale. A key objective of this paper is to demonstrate that when the concept of sustainability is unified, optimal outcomes across the tenets are often easily achievable and the preferred design option will not only be the most economically-, but also the most environmentally- and socially-friendly.

Following a cumulative approach, a method for quantification of the sustainable risk of alternatives is also presented. The physical meaning of sustainable risk reflects the anticipated impact of the alternative on the environmental-, social- and economic-tenets of sustainability. Control and management of pavement sustainability can aid in limiting these impacts.

The results presented in this paper show that even though sustainability is complex, simplification is achievable. These results add an additional metric that road authorities may apply to govern their respective pavement networks and make more reliable decisions regarding pavement alternatives designed for sustainable outcomes.

## 13 Recommendations

The model proposed in this paper is based on abstract principles and is unweighted, meaning the relative impact of key risks to each other and collectively to sustainability are equal. For the implementation of the model within specific road authority management systems, local stakeholder engagement and expert inputs are required to determine the weights relative to the community that both utilises and is affected by the road network. This should be accompanied by due recognition of the definitions of both risk and sustainability within the context of application. It is recommended that road authorities integrate the framework into their day-to-day management of pavements in South Africa and continuously improve the model for future use.

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