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Carbon accounting and economic analysis of sustainably sourced bio binders in NZ transport infrastructure: A new pan NZ "carbo-economic" analysis tool

Harisankar Menon[1], Doug Wilson[2], Satyanarayana Gattu[3]

[1]University of Auckland

[2] University of Auckland

[3] University College Dublin

Email for correspondence (presenting author): harisankar.menon@auckland.ac.nz

Abstract

The global shift toward sustainability and decarbonisation has amplified the need for innovative construction materials, particularly in infrastructure sectors historically dependent on fossil fuels. In New Zealand (NZ), this urgency is intensified by the 2020 closure of the Marsden Point refinery, which has significantly increased the nation's reliance on imported bitumen, posing environmental, economic, and supply chain vulnerabilities. This study explores the viability of bio binders—renewable materials derived from locally sourced biomass—as sustainable alternatives for NZ's Road infrastructure. Synthesising prior analysis of sustainable asphalt technologies, the paper introduces a novel, modular carbon accounting and life cycle assessment (LCA) purpose built for the NZ context. Unlike conventional spreadsheet-based models or those relying on overseas databases such as Eco invent, this tool is tailored to the nuances of New Zealand's carbon market and infrastructure standards. It ensures compliance with NZTA guidelines while allowing flexibility for integration with international standards. By addressing data reliability gaps prevalent across New Zealand's environmental reporting landscape, the tool aims to provide both carbon and economic analysis functionality. This work positions bio binders not only as a technical solution but as a strategic pathway toward resilient and low emission transport infrastructure in Aotearoa.

1 Introduction

The escalating global imperative toward sustainability and decarbonisation has spotlighted the importance of innovative construction materials, especially in infrastructure sectors reliant on fossil fuels (Tapper et al., 2024). New Zealand (NZ) exemplifies these challenges acutely, exacerbated by the 2020 closure of the Marsden Point refinery, significantly heightening the nation's dependency on imported bitumen (NZ Transport Agency Waka Kotahi, 2023). This reliance poses substantial environmental and economic risks, showing the urgency for alternative, sustainable binders in road infrastructure (Ministry for the Environment, 2023). The paper synthesises findings from an extensive analysis of sustainable asphalt materials that had previously been completed. It provides insights into bio binder development, performance, environmental impacts, and barriers to adoption using a novel carbon framework developed for the same.

The research builds on those learnings to develop a carbon framework and life cycle analysis tool that is not an Excel spreadsheet as is the case with most tools in this realm. This is particularly important for the New Zealand context as there are variations in the data that comes with life cycle analysis. These variations are especially notable when using European databases like Eco Invent for conducting LCA via SimaPro™[1] or GaBi™[2] or similar software/databases reporting on carbon emissions. This tool is built from the ground up, for the NZ carbon market and is compliant with local regulations, though packaged as modules to make each module have a different compliance standard that integrates with the rest of the core emissions data, thus widening the audience for this tool as many industries in NZ suffer from data reliability when it comes to emissions, an observation this author has made from reading environment reports of the all the large firms in NZ. This tool has been developed to comply with NZTA regulations in measuring the carbon emissions, in the subsequent economic analysis and modelling of NZ transport infrastructure.

2 Literature review

The diverse range of bio binder materials explored includes biochar, lignin, waste cooking oils, castor oil, microalgae derived oils, and swine manure derivatives (Yaro et al., 2023; Fini et al., 2019). Each material exhibits unique properties with varying performance in replacing or augmenting conventional bitumen in asphalt mixtures. Biochar, for instance, notably enhances binder stiffness, reduces aging susceptibility, and acts as a carbon sink (Zhou, 2024). Lignin derived binders similarly improve thermal stability and material durability (Gaudenzi et al., 2023). Waste derived oils, particularly waste cooking oils, have shown effective rejuvenating capabilities for reclaimed asphalt, though challenges persist regarding viscosity management at higher temperatures (Ferdaus et al., 2025). Innovative sources such as microalgae and hydrothermal liquefaction products merge sustainable biomass utilisation with strong mechanical performance, illustrating the growing potential for circular economic approaches in asphalt production (Borghol et al., 2018).

2.1 Environmental and economic implications

One of the most compelling arguments supporting locally sourced bio binder implementation revolves around substantial reductions in local greenhouse gas (GHG) emissions. Lifecycle assessments from multiple studies suggest that bio binders could achieve carbon emission reductions of up to 50%, primarily through integration with reclaimed asphalt pavement (RAP) that recycles existing materials on-site. The adoption of bio binders can have benefits of decreased production temperatures, reduced energy consumption, and long-term cost savings (Neaylon et al., 2019). Despite these advantages, the economic viability is impacted by variability in biomass feedstock quality, processing expenses, insufficient largescale application data, necessitating further economic feasibility analyses. There also exists the possibility that the NZ government may continue with traditional bitumen due to various reasons, ranging from budget constraints to insufficient binder performance; however, this study focuses more on providing the tool and the framework required to perform such research.

3 Methodology

To address critical gaps in current pavement assessment methodologies, this study develops an integrated carbon accounting framework that systematically combines mechanistic empirical modelling with real time economic optimisation. The methodology advances beyond existing fragmented approaches by establishing quantitative linkages

[1] SimaPro™ [1], https://simapro.com/

[2] GaBi™ [2], https://sphera.com/solutions/product-stewardship/life-cycle-assessment-software-and-data/

between pavement performance predictions, environmental impact assessments, and economic decision-making processes.

Integrated MEPDG-carbon framework

The methodology extends the Mechanistic Empirical Pavement Design Guide (MEPDG) beyond traditional pavement design performance modelling by incorporating dynamic carbon accounting throughout pavement asset management life cycles. Unlike conventional MEPDG applications that focus solely on structural performance, this framework quantifies the carbon implications of design decisions in one application, enabling simultaneous optimisation of performance and environmental outcomes. The framework implements PAS 2080 [3] compliance protocols to establish standardised carbon reduction pathways specific to New Zealand conditions. This integration allows practitioners to evaluate alternative material configurations and supply chain strategies within a single analytical environment, representing a methodological advancement over current practice, where carbon and performance assessments occur independently.

3.1 Multivariable sensitivity analysis with economic coupling

he sensitivity analysis component employs Monte Carlo simulation techniques to systematically evaluate parameter uncertainties across three interconnected domains: pavement performance, carbon emissions, and economic outcomes. This approach quantifies how variations in binder source and composition, climatic conditions, and traffic loading propagate through both environmental and economic metrics simultaneously. The methodology establishes sensitivity thresholds that identify when a bio binder material selection becomes economically favourable in comparison to traditional binder options while maintaining required performance standards. This provides decisionmakers with quantified implementation criteria rather than qualitative assessments typical of current practice.

3.2 Dynamic hotspot identification and intervention modelling

Hotspot evaluation modelling is a function in the tool developed to extend beyond static life cycle assessment by implementing dynamic impact tracking that responds to changing input parameters. The methodology identifies critical intervention points where targeted modifications yield maximum carbon reduction per unit economic investment, enabling resource allocation optimisation. This approach quantifies intervention effectiveness through integrated metrics that capture both immediate carbon benefits and long-term economic implications, providing a systematic basis for prioritising sustainability investments.

3.3 Shadow pricing integration with infrastructure economics

The economic analysis methodology incorporates multiple carbon pricing scenarios (offset markets, emissions trading schemes, carbon taxation) to evaluate project viability under varying policy conditions. This approach enables infrastructure planners to assess project resilience to carbon pricing volatility while optimising material selection strategies. The framework calculates scenario specific Internal Rate of Return and Net Present Value metrics that incorporate carbon costs, providing quantified economic justification for bio binder adoption under different regulatory environments.

[3] PAS2080: https://www.standards.govt.nz/shop/pas-20802023

3.4 Framework validation and performance verification

The carbon accounting tool underwent systematic validation through comparison with established LCA software (SimaPro™, GaBi™) using identical input datasets from three completed New Zealand infrastructure projects. Validation metrics demonstrated consistency within 5% for carbon calculations across the EN15804 (as seen in Figure 1) framework stages (A1–A5, B1–B7, C1–C4, D). Performance verification involved sensitivity testing against known parameter variations, confirming the framework's responsiveness to input changes aligns with theoretical expectations. Economic module validation compared outputs against traditional NPV calculations for projects with documented carbon costs, achieving correlation coefficients exceeding 0.95. The integrated methodology represents a systematic advancement over current practice by providing quantified, real time assessment capabilities that enable simultaneous optimisation of performance, environmental, and economic objectives within infrastructure decision making processes.

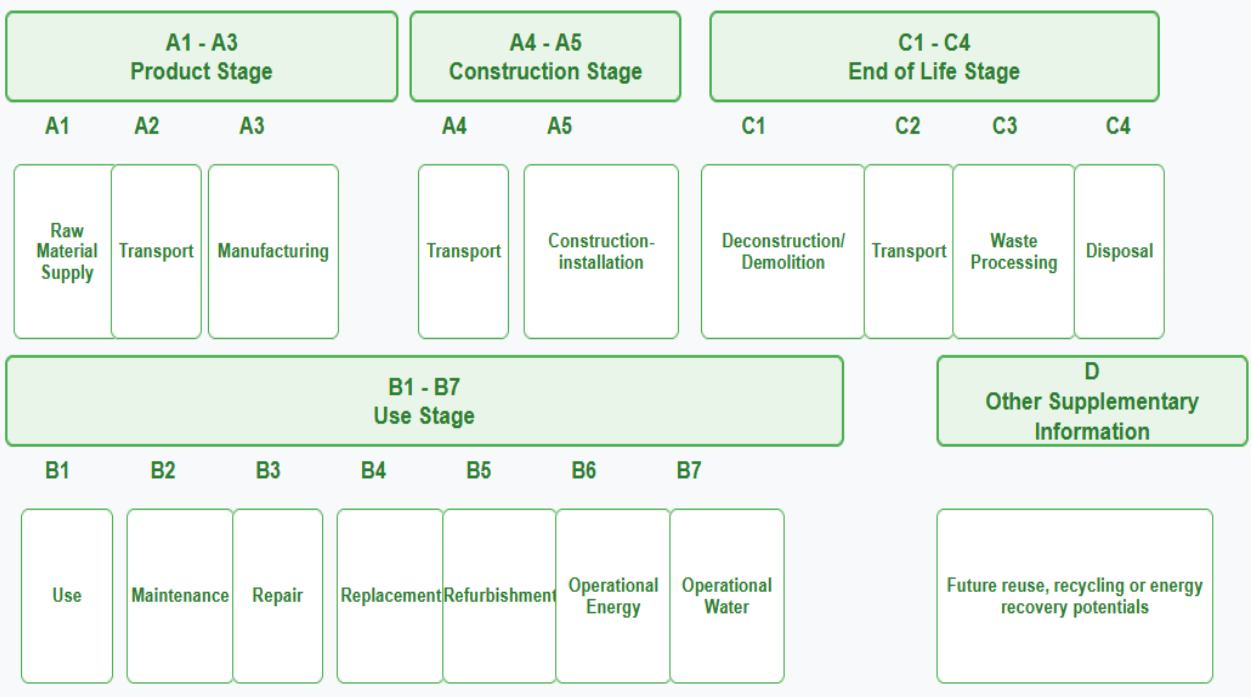

Figure 1: EN15804 Standard for EPD production used as inspiration for cradle to grave analysis, (image generated using AI on the prompt for EN15804 model).

4 Process flow for the framework:

This section describes the framework that has been developed to demonstrate the process steps, the data inputs and the outputs of analysis and how this can reform decision making. It is divided into the six sections as can be seen in Figure 2, that will go through the data flow in the framework and tool in the subsequent order.

4.1 Data input and processing

Users upload country specific environmental product declaration (EPD) data from Excel files. The tool extracts emission factors, mass data, and process labels, transforming them into usable entries for each lifecycle module with respect to the EN15804 standard. Each process or material is assigned and mapped to the correct

EN15804 module, allowing systematic tracking of raw material supply, manufacturing, construction, use, and end of life phases.

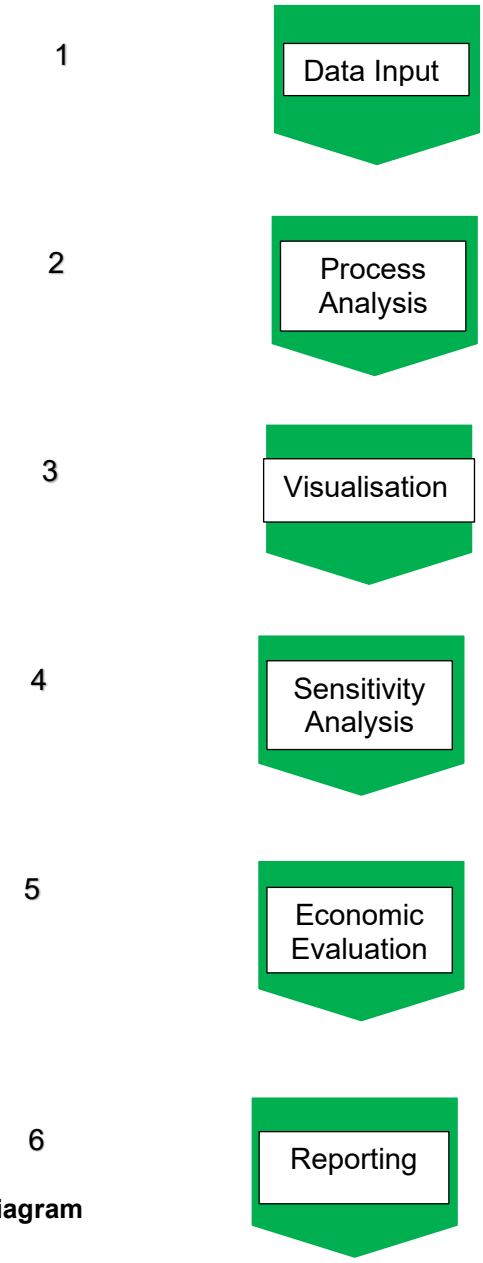

Figure 2: Data Flow Diagram

4.2 Visualisation

The tool generates real time flow diagrams (using React Flow), bar charts, and pie charts to illustrate emission contributions across modules and materials. Custom EPDs can be input manually if no reported EPDs have been developed or is available (as shown in Figure 3), and bio binder comparisons are displayed with colour coding for easy interpretation.

Figure 3: Orange dictates custom EPDs and Green colour defines EPDs from national carbon emissions database.

4.3 Hotspot and sensitivity analysis

The code enables sensitivity analysis by allowing users to adjust mass or emission factors for individual processes and observe immediate effects on total emissions. Hotspot analysis is visualised through bar and pie charts, helping identify modules or processes with the largest environmental impact (As shown in Figure 4). It can then be replaced with some other process that is more sustainable. It helps us understand where most emissions lie within the entire project and allows for optimisation of those processes causing said emissions with alternative processes that can help reduce emissions.

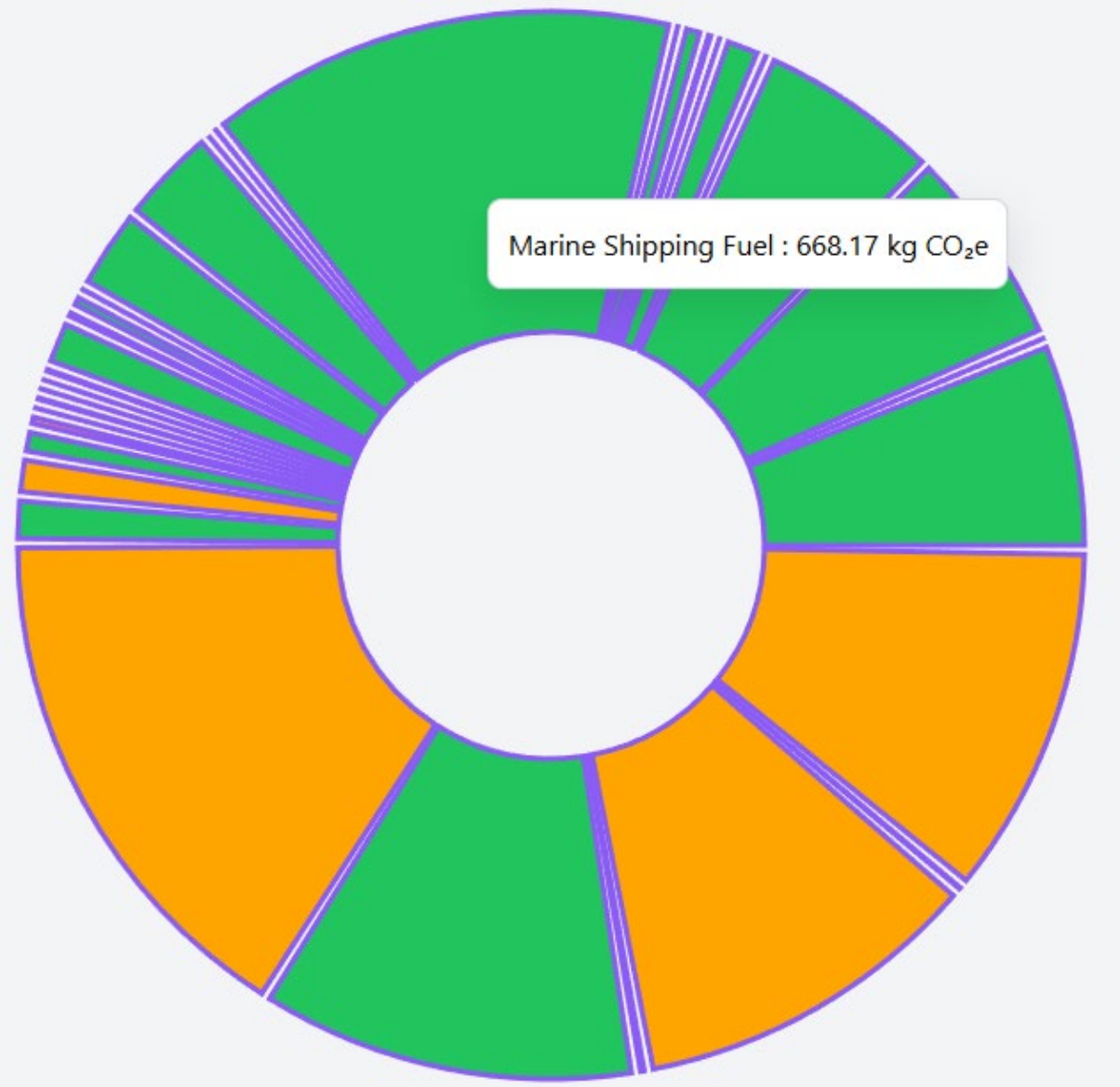

Figure 4: Orange dictates custom EPDs and Green colour defines EPDs from national carbon emissions database, the pie chart shows reliability by the nature of the EPDs used.

4.4 Reduction and economic analysis

A dedicated dashboard evaluates potential emission reductions from bio binder use and presents simple economic analysis (as can be seen in Figure 6) to compare alternative scenarios and to apply the best ecofriendly and economic friendly results onto the rest of the framework (As can be seen in Figure 5).

Figure 5: Reduction Analysis helps find alternatives for heavy emissions

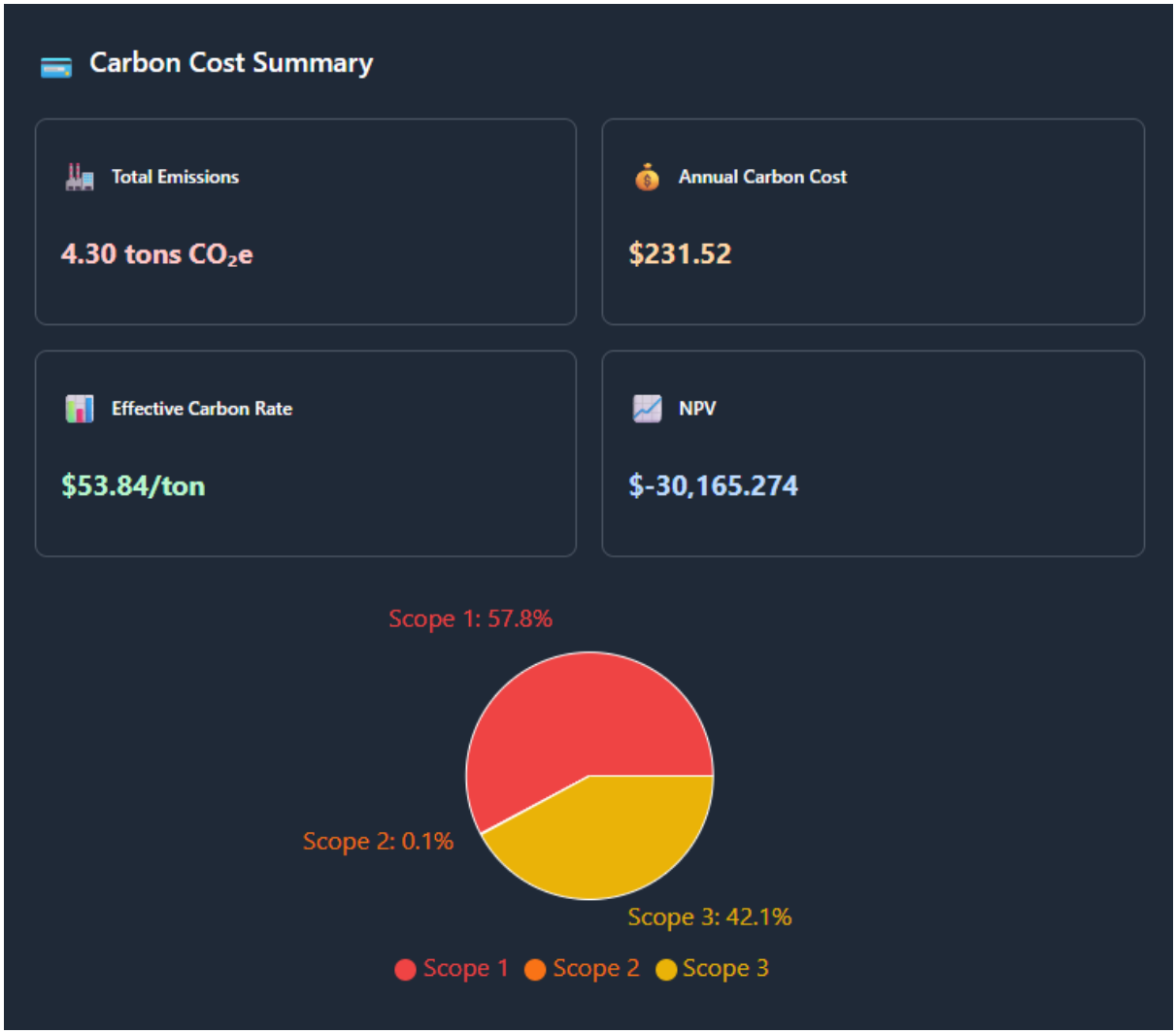

Figure 6: Economic analysis based on input emissions and project cost specifics provides economic analysis.

4.5 Reporting

Users can export full system diagrams and emission summaries as PDFs (as can be seen in Figure 7), ensuring the results are documented and ready for stakeholder presentation or policy use. In the context of this study, this tool integrates seamlessly with the MEPDG modelling, sensitivity analysis, and hotspot evaluation described in the methodology, transforming theoretical findings into interactive, data driven assessments. This connection

strengthens the study's ability to bridge laboratory findings with applied carbon accounting, ultimately supporting the evaluation of bio binder alternatives for sustainable infrastructure.

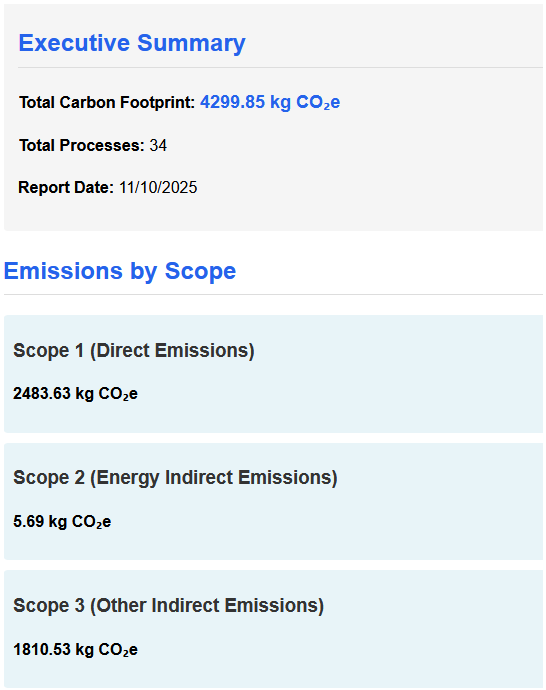

Figure 7: Report generated by the tool covers all details of emissions that helps with auditing.

5 The underlying framework for the tool

5.1 Scope definition

In conducting a robust life cycle assessment (LCA) of pavement systems, it is essential to define the scope of the study clearly and systematically. Figure 8 presents the framework used to guide the scope definition process in this research. The framework is divided into two primary components: defining the system boundary and setting the functional unit (FU).

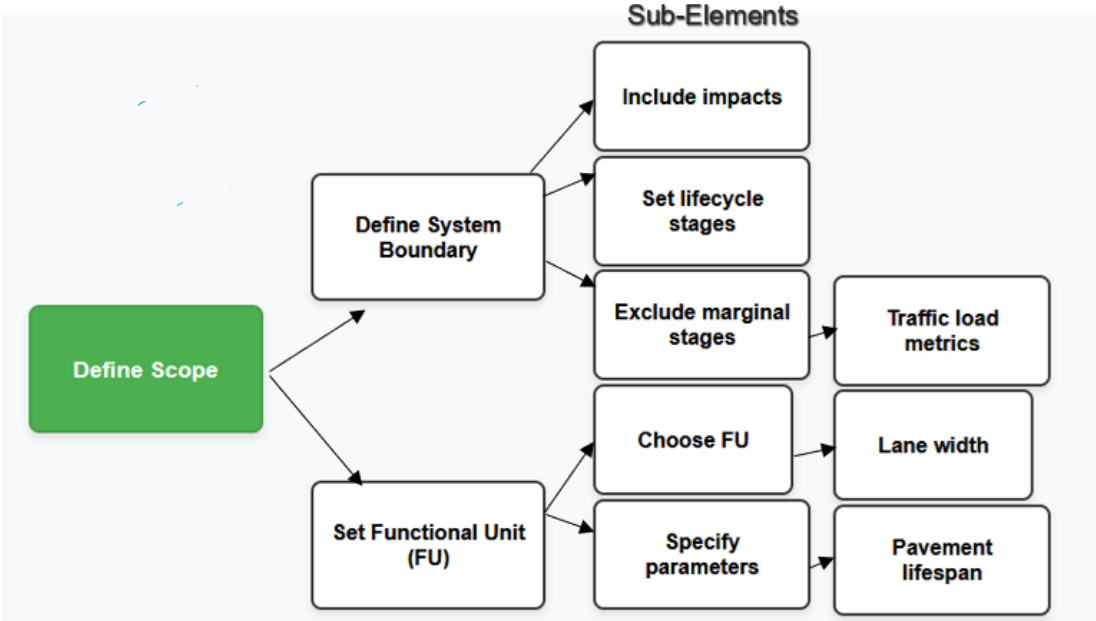

Figure 8: Identifying the boundaries

5.1.1 Defining the system boundary

Defining the system boundary is a foundational step in life cycle assessment that establishes the scope and limits of what will be analysed in a pavement study. This process involves making deliberate decisions about what to include and exclude from the analysis, which ultimately shapes the comprehensiveness and focus of the environmental assessment.

The first critical component involves identifying and including the relevant environmental impacts that will be measured throughout the study. This requires careful consideration of which environmental performance indicators are most meaningful for the specific pavement system being evaluated. Greenhouse gas emissions typically serve as a primary indicator, capturing the carbon footprint across various activities from material extraction to construction and beyond. Energy consumption represents another vital metric, tracking how much energy is required at each stage of the pavement's existence. Material use must also be documented, accounting for the extraction and processing of raw materials like aggregates, asphalt, cement, and other components. These impacts form the core of what the assessment will measure and compare, providing quantifiable data that can inform decision-making about pavement design and construction methods.

The second element focuses on determining which stages of the pavement life cycle will be incorporated into the assessment. This involves mapping out the entire journey of the pavement from conception to disposal and deciding which phases warrant detailed analysis. The raw material supply stage examines the extraction and initial processing of materials needed for pavement construction. The manufacturing phase looks at how these raw materials are transformed into usable pavement components, such as the production of asphalt mixtures or concrete. The construction stage evaluates the environmental impacts associated with building the pavement, including equipment operation and transportation. The use phase considers the long-term operational period when the pavement serves its intended function, which may include factors like vehicle-pavement interaction and its influence on fuel consumption. Maintenance activities throughout the pavement's service life constitute another important stage, encompassing repairs, resurfacing, and rehabilitation efforts. Finally, the end-of-life stage addresses what happens when the pavement reaches the conclusion of its useful life, including demolition, disposal, or recycling possibilities.

The third essential element involves making transparent decisions about what to exclude from the analysis. Not every process or stage contributes meaningfully to the overall environmental impact and attempting to include everything can make the assessment unwieldy and potentially obscure the most significant factors. Processes that contribute negligibly to the total environmental burden may be legitimately excluded, particularly when their inclusion would require disproportionate effort relative to the insight gained. Data availability also plays a practical role in these decisions, as some processes may lack reliable information for accurate assessment. The key principle here is transparency, any exclusions must be explicitly documented and justified. For instance, if certain equipment used during construction has minimal emissions compared to the major machinery involved, or if a particular subprocess can be bypassed in the operational context without affecting the core function, these omissions should be clearly stated. Similarly, if a process is not directly attributable to the pavement system because its connection is too indirect or its emissions are vanishingly small, excluding it helps maintain focus on the factors that truly drive environmental performance. This selective approach ensures that the assessment remains manageable while still capturing the essential environmental dynamics of the pavement system under study.

5.1.2 Setting the functional unit (FU)

The functional unit represents a critical reference point in life cycle assessment that allows for meaningful quantification of environmental impacts and provides the foundation for comparing different pavement alternatives on an equal basis. Without a well-defined

functional unit, it would be impossible to make valid comparisons between different pavement designs or construction methods because the scale and scope of what is being measured would vary inconsistently.

The first essential task in establishing the functional unit involves selecting an appropriate metric that accurately reflects how the pavement system will function and deliver value. This choice must align with the practical realities of pavement design and the specific objectives of the assessment. One common approach is to define the functional unit per kilometre of pavement, which proves particularly useful when comparing linear infrastructure projects or evaluating different pavement types for similar roadway lengths. Alternatively, expressing the functional unit per square meter offers advantages when the focus is on pavement area rather than length, which can be relevant for projects where width variations are significant or when analysing specific pavement sections. Another valuable option is defining the functional unit per year of service, which emphasises the temporal dimension of pavement performance and can help account for differences in durability and longevity between alternatives. The chosen functional unit must capture the essential purpose the pavement serves, whether that involves providing a durable driving surface, accommodating specific traffic volumes, or maintaining performance standards over time. This selection fundamentally shapes how all subsequent environmental impacts will be normalised and presented.

The second crucial task involves specifying the parameters that characterise the pavement system and influence its environmental performance. These parameters provide the detailed context necessary to understand what the functional unit represents in practical terms. Traffic load metrics constitute a primary consideration, requiring careful quantification of the expected vehicle types that will use the pavement and the volumes of traffic it must accommodate. This includes distinguishing between light passenger vehicles, heavy commercial trucks, and other vehicle categories, each of which imposes different stresses on the pavement structure and influences design requirements. The intensity and composition of traffic directly affect material quantities needed, structural thickness, and maintenance frequency, all which cascade into environmental impacts. Lane width represents another fundamental parameter that must be clearly specified, as it determines the physical extent of the pavement surface being constructed and maintained. Wider lanes or additional lanes mean more materials, more construction effort, and potentially greater environmental burden, so this dimension must be explicitly stated to ensure comparisons remain valid. Pavement lifespan stands as perhaps the most influential parameter, representing the estimated duration that the pavement will provide adequate service before requiring major rehabilitation or complete reconstruction. This temporal dimension profoundly affects the environmental profile because a longer-lasting pavement may justify higher initial material or energy investments that are amortised over extended service periods, while a shorter-lived pavement might require more frequent interventions that accumulate environmental impacts over time. Together, these parameters create a comprehensive specification that transforms the abstract functional unit into a concrete representation of the pavement system being assessed, ensuring that environmental impacts can be properly attributed and compared across different design alternatives.

5.2 Input data collection

Accurate and context specific input data are essential to conducting a reliable life cycle assessment (LCA) of pavement systems. Figure 9 illustrates the structured framework employed in this study to collect and organise input data across three major categories: local emission factors, traffic data, climate factors, and trade and supply chain dynamics.

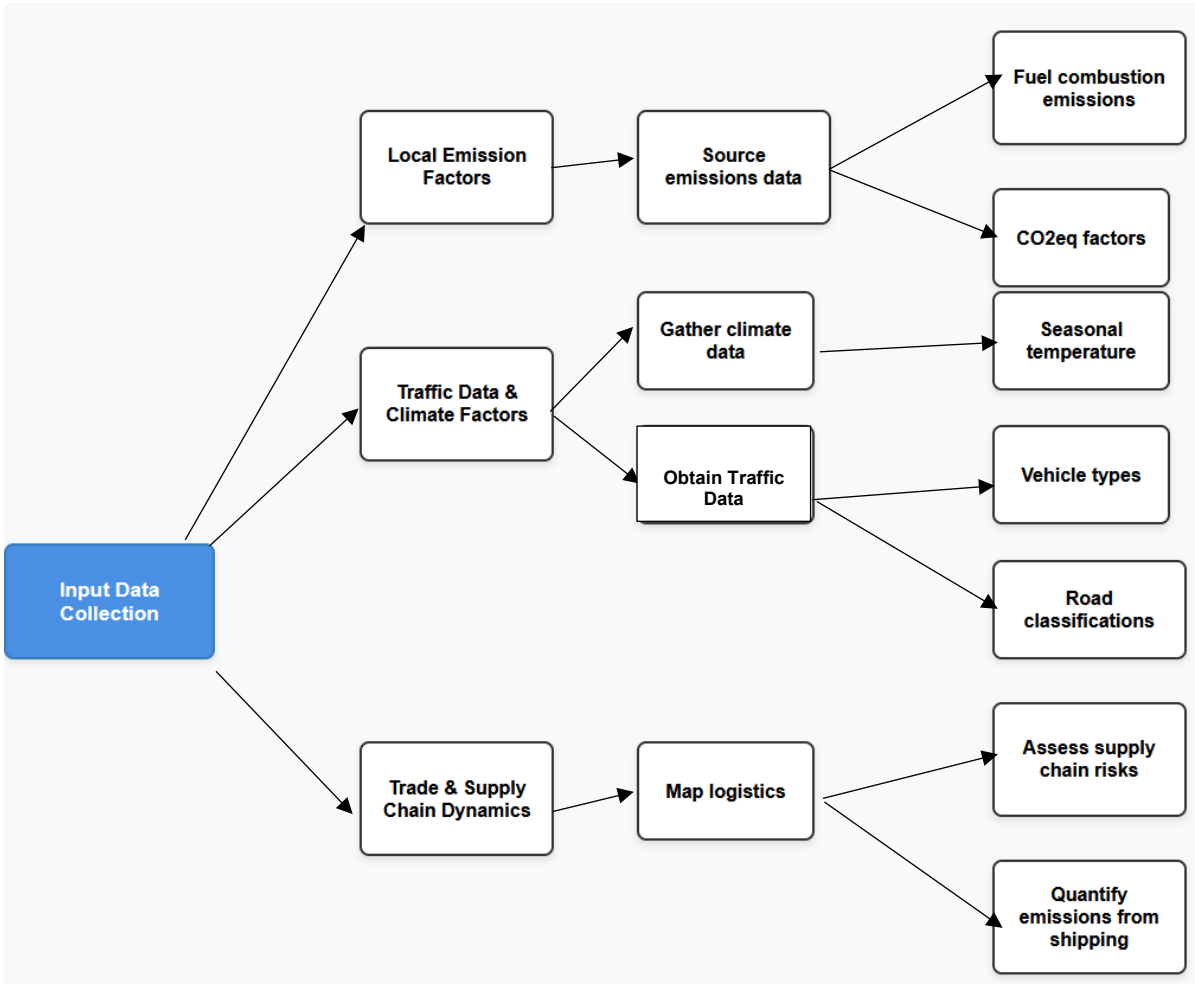

Figure 9: Input Data Collection

5.2.1 Local emission factors

Local emission factors play a vital role in ensuring that the life cycle assessment accurately reflects the specific environmental context in which the pavement project will be constructed and operated. Rather than relying on generic or global averages, gathering region-specific emission factors allows the assessment to capture the unique characteristics of local energy systems, fuel sources, manufacturing processes, and environmental conditions that can significantly influence the actual environmental impacts of pavement construction and maintenance activities.

The process of sourcing emissions data requires comprehensive collection of information related to fuel combustion emissions, which represent one of the primary sources of environmental impact in pavement-related activities. This data encompasses the emissions generated when various fuels are burned to power construction equipment, transport materials, operate manufacturing facilities, and conduct maintenance operations. Different regions may have different fuel compositions, quality standards, and combustion efficiencies that affect the emission profiles of these activities. The collection must also account for carbon dioxide equivalent factors, which provide a standardised way to express the global warming potential of various greenhouse gases by converting them into equivalent amounts of carbon dioxide. This conversion is essential because combustion and industrial processes release not only carbon dioxide itself but also other climate-forcing gases such as methane and nitrous oxide, each with different atmospheric lifetimes and warming potentials.

The emphasis on ensuring appropriate representation of both direct and indirect emissions reflects the need for comprehensive accounting that captures the full scope of environmental impacts. Direct emissions are those that occur immediately and obviously from specific

activities, such as the exhaust from a diesel-powered paving machine or the emissions from an asphalt plant's burner. These are relatively straightforward to identify and quantify because they occur at the point of fuel consumption. Indirect emissions, however, require more careful consideration because they occur upstream or downstream of the immediate activity being assessed. These might include emissions associated with extracting and refining the fuel before it reaches the construction site, emissions from generating the electricity used in material processing facilities, or emissions from producing the equipment and machinery used in construction. By gathering local data that accounts for both direct and indirect emissions, the assessment achieves a completer and more accurate picture of the environmental burden associated with the pavement system, reflecting the actual conditions and practices of the region where the project will be implemented rather than relying on potentially misleading generic assumptions.

5.2.2 Traffic data and climate factors

Understanding the intricate relationship between traffic patterns and climate conditions forms a crucial component of accurately estimating both pavement performance and the associated environmental impacts throughout the pavement's life cycle. These two factors are deeply interconnected, as climate affects how pavements respond to traffic loading, while traffic characteristics determine the magnitude and nature of stresses that pavements must endure under varying climatic conditions. Together, they shape decisions about pavement design, material selection, maintenance scheduling, and ultimately the environmental footprint of the entire system.

Gathering comprehensive climate data represents an essential step in this process, with particular attention paid to seasonal temperature variations that can dramatically affect pavement behaviour and longevity. Temperature fluctuations throughout the year influence pavement materials in multiple ways that cascade into environmental consequences. In asphalt pavements, high summer temperatures can cause softening and rutting, while low winter temperatures can lead to thermal cracking and increased brittleness.

5.2.3 Trade and supply chain dynamics

Obtaining detailed traffic data provides the other critical dimension needed to understand pavement environmental performance, as traffic characteristics fundamentally determine the structural demands placed on the pavement and influence both its design requirements and deterioration rate. This data collection focuses on capturing information about vehicle types, which is essential because different vehicles impose vastly different loads on pavement structures. Heavy commercial trucks, with their multiple axles and substantial gross weights, create far more pavement damage per pass than light passenger vehicles, following a relationship that is often exponential rather than linear. The mix of vehicle types using a particular roadway therefore significantly affects how robust the pavement structure must be, influencing the quantity and type of materials required, the thickness of various pavement layers, and the frequency of maintenance interventions needed to maintain acceptable service levels. Road classifications provide additional context that helps characterise traffic patterns more completely, as highways, arterial roads, collector streets, and local roads each experience different traffic volumes, vehicle compositions, and loading patterns. A highway carrying predominantly heavy freight traffic presents entirely different structural and environmental considerations than a residential street serving primarily light vehicles. This classification information also helps predict traffic growth patterns over time, as different road types typically experience different rates of traffic increase that affect long-term pavement performance and maintenance needs. By collecting comprehensive traffic data that captures this diversity of traffic loads and their respective characteristics, the assessment can more

accurately attribute environmental burdens to the actual demands being placed on the pavement system, ensuring that design decisions appropriately balance structural requirements with environmental considerations and that comparisons between pavement alternatives reflect realistic operating conditions.

5.3 LCA subsystems

To ensure a comprehensive and structured life cycle assessment (LCA) of pavement systems, the study decomposed the system into distinct subsystems. Figure 10 shows the framework used to capture the full range of material, energy, and emissions flows across the pavement life cycle, from raw material extraction to end of life management.

5.3.1 Raw material extraction The raw material extraction subsystem includes the extraction and preparation of raw materials. This involves analysing bio binder production through assessment of biobased binder production processes, including energy use and emissions. It also encompasses bitumen extraction and refining, which involves evaluation of the environmental impacts associated with the extraction, refining, and preparation of petroleum-based bitumen.

5.3.2 Transportation

The transportation subsystem addresses the movement of materials and products between life cycle stages. This involves modelling logistics emissions through estimation of emissions from the transport of raw materials, intermediate products, and final materials to the construction site.

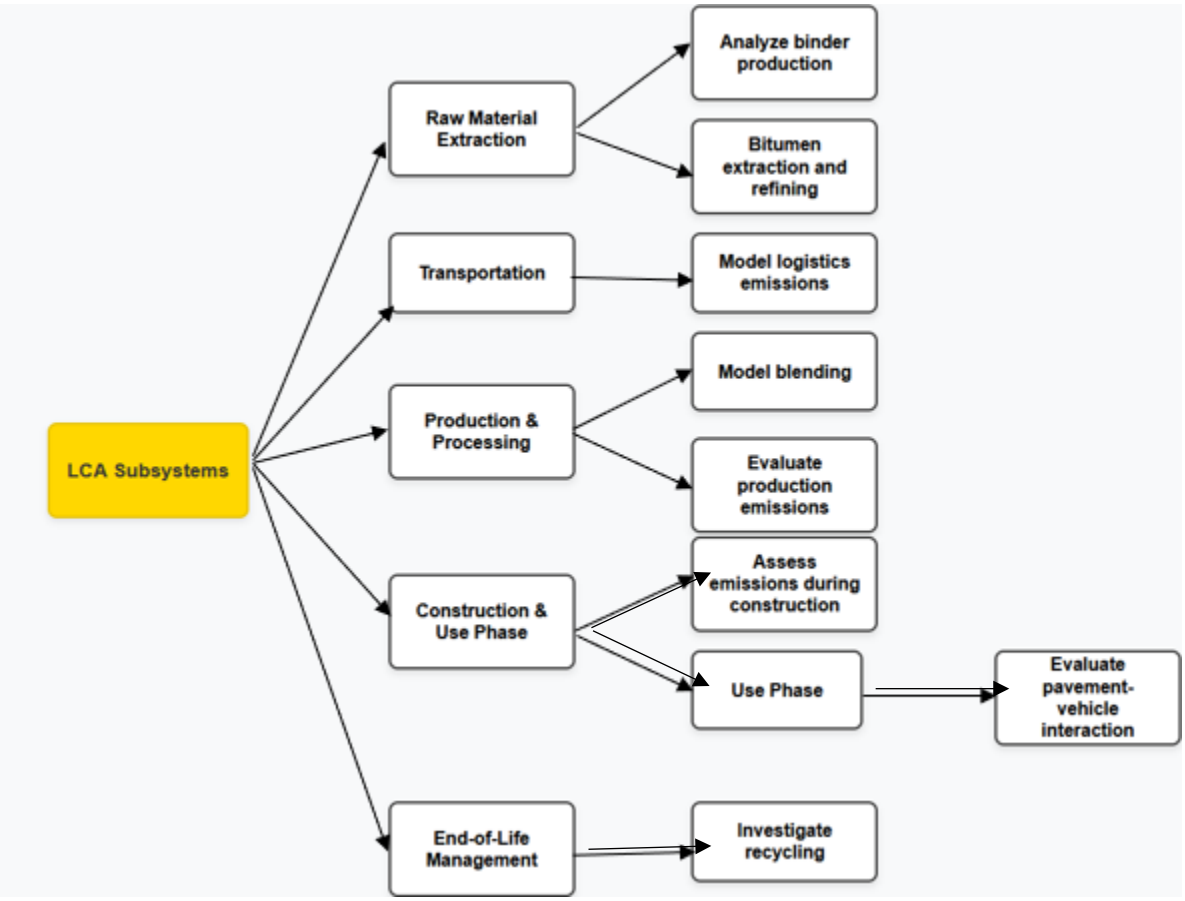

Figure 10: The LCA subsystem

5.3.3 Production and processing

This subsystem captures the impacts associated with material manufacturing and preparation. It involves modelling the blending processes through assessment of the blending operations required for binder preparation. Additionally, it includes evaluating production emissions by quantifying the emissions and resource consumption that occur during manufacturing, mixing, and material processing activities.

5.3.4 Construction and use phase

This subsystem addresses impacts during pavement installation and operation. It involves assessing emissions during construction through evaluation of energy use, material losses, and emissions that occur during construction activities. The use phase component examines operational impacts, particularly through evaluating pavement vehicle interaction by analysing how pavement characteristics influence vehicle fuel consumption and emissions over the use phase.

5.3.5 End of life management

The end-of-life management subsystem examines the final stage of the pavement life cycle, addressing what happens when the pavement reaches the conclusion of its service life and can no longer adequately fulfil its intended function. This critical phase determines whether materials are simply discarded as waste or whether value can be recovered through various end-of-life strategies that may significantly affect the overall environmental profile of the pavement system.

Investigating recycling processes forms a central component of this subsystem, as it explores the potential for reclaiming pavement materials and reintroducing them into productive use rather than consigning them to landfills. This investigation requires detailed assessment of the technical processes involved in recycling, which may include milling or crushing operations to break down the existing pavement structure, separation techniques to isolate different material fractions, and processing methods to prepare recovered materials for reuse in new pavement construction or other applications. The viability and environmental benefits of recycling depend heavily on the specific technologies employed and the quality of materials that can be recovered.

Material recovery represents another essential consideration within this subsystem, focusing on how much of the original pavement material can be successfully reclaimed and what proportion retains sufficient quality for meaningful reuse. Recovery rates vary considerably depending on pavement type, with some materials like asphalt demonstrating high recyclability when proper techniques are applied, while other components may be more challenging to recover effectively. The assessment must quantify not only the mass of materials recovered but also evaluate whether recovered materials can substitute for virgin materials on a one-to-one basis or whether their properties require supplementation with fresh materials or additives to achieve necessary performance standards.

Disposal impacts must also be thoroughly evaluated for materials that cannot be recycled or recovered, encompassing the environmental consequences of transporting waste materials to disposal sites, the land use implications of landfilling, potential leachate generation that might contaminate groundwater, and any emissions associated with the decomposition or long-term environmental presence of discarded pavement materials. By comprehensively examining these recycling, recovery, and disposal pathways, the end-of-life management subsystem provides crucial insights into how pavement systems can be designed and managed to minimise waste and environmental burden even after their primary service life concludes.

5.4 Analysis framework

The analytical phase of the study integrates multiple assessment approaches to ensure a comprehensive understanding of pavement life cycle performance and environmental impacts. Figure 11 illustrates the structured framework used to conduct the analysis, which includes mechanistic empirical analysis, sensitivity analysis, and hotspot evaluation.

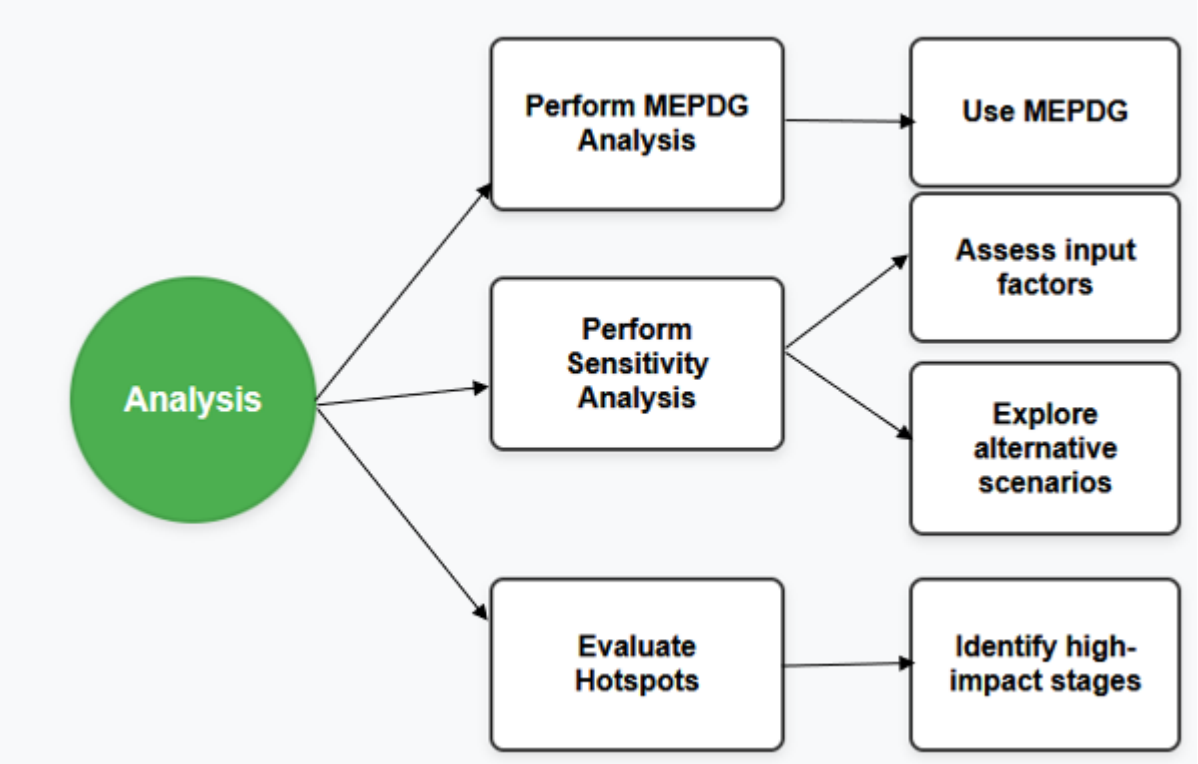

Figure 11: Analysis

5.4.1 Perform MEPDG analysis

The Mechanistic Empirical Pavement Design Guide, commonly known as MEPDG, was employed to model pavement performance under various conditions throughout its service life. The application of MEPDG tools and methodologies allowed the study to estimate pavement distress, structural performance, and longevity by incorporating both traffic and climate inputs. This analytical framework combines mechanistic principles that describe how pavements respond to loads and environmental stresses with empirical observations of actual pavement behaviour in the field. The traffic inputs, including vehicle types, axle loads, and traffic volumes, along with climate data encompassing temperature variations and precipitation patterns, are processed through the MEPDG framework to calculate cumulative damage and predict how the pavement will perform over time. This integration produces region-specific performance predictions that reflect actual operating conditions, ensuring that the subsequent life cycle assessment builds upon realistic expectations of pavement behaviour and maintenance requirements.

5.4.2 Perform sensitivity analysis

Sensitivity analysis was conducted to assess the robustness of results and to explore the influence of key parameters on the overall findings of the life cycle assessment. This involved assessing input factors through identification and evaluation of critical input variables, such as material properties, traffic loads, and climate conditions, that may significantly affect outcomes. The analysis also included exploring alternative scenarios by simulating different design or material options to evaluate how responsive system

performance and environmental impacts are to varying assumptions. By systematically varying these parameters and observing how results change, the sensitivity analysis reveals which variables have the greatest effect on outcomes, where data quality matters most, and whether key findings remain valid across a reasonable range of assumptions.

5.4.3 Evaluate hotspots

A hotspot evaluation was undertaken to identify the most impactful stages or processes within the life cycle of the pavement system. This evaluation focused on identifying high impact stages by pinpointing the subsystems or phases, such as material production, construction, or the use phase, that contribute disproportionately to total emissions or resource consumption. By systematically analysing the relative contribution of each life cycle stage to the overall environmental burden, the hotspot evaluation reveals where the greatest environmental impacts occur and helps prioritise areas for improvement. This targeted approach ensures that efforts to reduce environmental impacts focus on the stages where changes will yield the most substantial benefits rather than distributing attention evenly across all phases regardless of their relative importance.

5.5 Monetisation and recommendations

To translate the technical findings of this study into actionable strategies, the final phase focused on monetisation and policy recommendations. As shown in Figure 12, this framework emphasises the economic and regulatory potential of sustainable materials, particularly bio binders, within the New Zealand context.

5.5.1 Highlight bio binder scalability

Recognising the transformative potential of bio binders, this study outlines pathways to support their broader adoption in pavement construction. A key recommendation involves promoting public private partnerships by encouraging collaboration between government, industry, and academia to fund research, pilot projects, and infrastructure upgrades. These partnerships can leverage the strengths of each sector, with government providing regulatory support and initial funding, industry contributing practical expertise and commercial viability assessments, and academia offering research capabilities and innovation. Additionally, the study emphasises the need to develop strategy by establishing national deployment roadmaps and long-term strategies to scale up bio binder production and use. These strategic frameworks would provide clear direction for expanding bio binder manufacturing capacity, creating supply chains, establishing quality standards, and systematically integrating bio binders into mainstream pavement construction practices, thereby transitioning these materials from niche applications to widespread commercial viability.

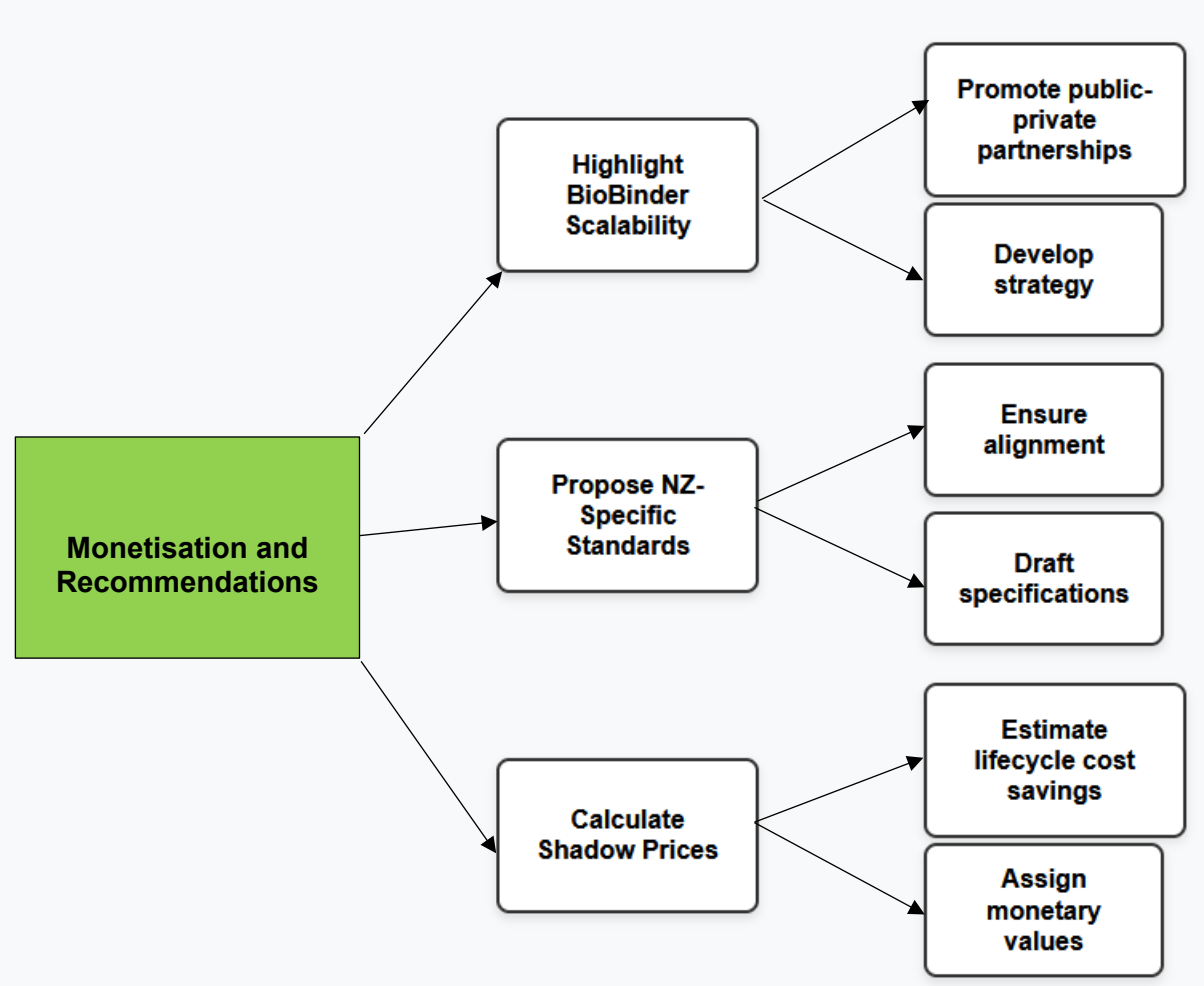

Figure 12: Monetisation and recommendations

5.5.2 Propose Specific standards

To ensure relevance and consistency, the study recommends the formulation of localised technical standards and guidelines specifically adapted to the regional context. This involves ensuring alignment by coordinating new standards with existing national sustainability goals, infrastructure resilience targets, and emission reduction pathways so that bio binder adoption supports broader environmental and policy objectives rather than operating in isolation. The development process should also include drafting specifications that are tailored to New Zealand's unique materials, climate conditions, and transport demands. These specifications would account for local aggregate types, regional temperature ranges and weather patterns, traffic characteristics specific to New Zealand roadways, and other factors that influence pavement performance. By creating standards that reflect actual local conditions rather than simply adopting generic international guidelines, the approach ensures that bio binder pavements will perform reliably and deliver the expected environmental benefits within the specific context where they will be deployed.

5.5.3 Calculate shadow prices

Economic viability is a critical driver for adoption, and therefore the study incorporates monetisation of environmental benefits using shadow pricing to make the case for bio binders more compelling from a financial perspective. This approach involves estimating lifecycle cost savings by quantifying the long-term cost advantages of using bio binders, including potential reductions in maintenance frequency and intensity as well as savings associated with lower emissions throughout the pavement's service life. These calculations

capture not only the direct construction costs but also the cumulative financial implications of enhanced durability, extended service life, and reduced environmental remediation needs. The study also emphasises the importance of assigning monetary values to carbon savings and other environmental benefits by applying economic valuations that translate emission reductions and ecological improvements into concrete financial terms. By attaching dollar values to avoided carbon dioxide emissions, reduced air pollution, and other environmental gains, this monetisation supports comprehensive cost benefit analysis and enables investment decisions that account for both conventional financial returns and the economic value of environmental performance, ultimately making bio binders more attractive to decision-makers who must justify expenditures based on total lifecycle value rather than initial capital costs alone.

6 Conclusion

Bio binders represent a significant opportunity to advance sustainable and resilient road infrastructure development in New Zealand. The integration of these renewable materials into asphalt production offers substantial potential for carbon emission reductions, decreased economic dependence on imported petroleum-based materials, and meaningful contributions to national decarbonisation objectives. However, the widespread adoption of bio binders faces considerable technical, economic, and regulatory challenges that necessitate comprehensive, multidisciplinary research and development initiatives. Current assessment procedures in infrastructure development suffer from fragmented approaches that evaluate environmental and economic factors in isolation, limiting decisionmakers' ability to optimise both sustainability outcomes and financial performance simultaneously. The carbon framework and analytical tool developed in this study address these procedural limitations by providing an integrated assessment methodology that enhances existing evaluation processes in several keyways.

First, the framework enables real time sensitivity analysis across multiple variables, allowing practitioners to immediately understand how changes in material composition, transportation distances, or production methods affect both carbon footprints and project economics. This capability represents a substantial improvement over current static assessment procedures that require separate analyses and manual correlation of results.

Second, the tool's scenario modelling functionality enables comparative assessment of bio binder implementation strategies against conventional approaches, providing quantified projections of environmental benefits alongside economic trade-offs over project lifecycles. This enhancement allows infrastructure planners to optimise material selection and procurement strategies based on comprehensive data rather than intuitive approximations or incomplete assessments.

Third, the framework's dynamic visualisation capabilities transform traditional assessment outputs from static reports into interactive decision support tools. Practitioners can manipulate parameters in real time to understand threshold conditions where bio binder adoption becomes economically favourable while maintaining environmental benefits, thereby identifying optimal implementation windows and strategies.

The integrated methodology addresses critical gaps in current assessment procedures by providing standardised metrics that enable direct comparison between projects and materials, facilitating evidence-based policy development and procurement decisions. This standardisation capability is particularly valuable for regulatory bodies and industry stakeholders seeking to establish performance benchmarks and incentive structures for sustainable infrastructure development. Furthermore, the framework's accessibility design

enables broader adoption across organisations with varying technical expertise, thereby democratising sophisticated assessment capabilities that were previously limited to specialised consultants or research institutions. This democratisation represents a significant enhancement to current procedures by enabling more widespread and consistent application of comprehensive sustainability assessments throughout the infrastructure sector.

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