Towards Sustainable Pavement Management

A Stochastic LCA Framework for Maintenance and Rehabilitation

EngD Thesis

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Towards Sustainable Pavement Management
EngD Project Report

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PREFACE

I'm happy to share this EngD report with you. It's the result of years of dedication, learning from mistakes, and certainly not giving up. The journey to this point has been tough, but it's been worth it. Things didn't always go the way I hoped, there were lots of obstacles and challenges, but here I am, showing what I've learned in a field I've grown to value.

I must stress that this achievement wouldn't have been possible without the guidance and support of my supervisors: Joao, Andreas, Fiola, and Rob. I can't thank them enough for their guidance and encouragement, but especially for their patience – a virtue beyond measure.

I extend a profound thank you to Joao, whom I deeply value and admire. His support and trust in me mean everything to me. Words fall short in expressing my appreciation for everything he's done—whether celebrating small victories with me, offering support during moments of doubt, or consistently pushing the boundaries of what I deemed achievable. Joao is the best.

I also want to take Andreas, not only for affording me this opportunity, but also for seeing something good about me and entrusting me with yet another project. Thanks to Fiola too, who exceeded the role of a typical supervisor. Our little chats that extended beyond work and the project made me feel at ease. They reminded me that at the end of the day, we are just people doing our thing. My appreciation extends to Rob as well, for his commitment to the project and willingness to help, and always with a smile.

I'm also deeply thankful for my family and friends. Thanks to my mom and my sister Victoria, for literally everything. And dad, I have no words, my hope is that you'd be happy. Special mentions go to Oleks and Dasha, my Enschede family. You always had my back and made me smile. I'd also like to thank Tim, my office partner in crime during the early research days, and Angie, who made our corner of the office feel like a home away from home. To my colleagues Shen, Maria, Ida, Irfan, Mohsen, and everyone else, you made this journey more enjoyable. And Kees, you deserve the biggest thank you. Your support during all those long hours, your pep talks when I felt down, and just having you around with Boris made everything easier.

As I share this research with the world, my hope is that it sparks conversations and inspires others to explore how we manage pavements and their impact on the environment. Let's do better for our world!

Once again, a big thanks to everyone who supported me in this adventure. Your help me made this research possible.

With heartfelt gratitude,

Andrea

EXECUTIVE SUMMARY

Integrating environmental performance into pavement management (PM) is key to improve Rijkswaterstaat (RWS) operations, given the cumulative environmental impacts resulting from recurring maintenance and rehabilitation (M&R) cycles and their contribution to total RWS emissions. Life cycle assessment (LCA) is a widely recognized approach applied to evaluate these impacts and inform decision-making in PM. However, its applicability to early PM stages within the RWS setting, where network-level plans are formulated, requires further investigation. Moreover, the validity of LCA in PM is often called into question for two reasons, 1) most pavement LCA studies tend to exclude important processes from the analysis, particularly related to pavement-vehicle interaction (PVI) effects during the use phase, and 2) they ignore the influence of uncertainty on the results.

PVI refers to the relationship between pavement rolling resistance (RR) and fuel economy. As RR increases, so do the fuel consumption and the emissions generated by the vehicles travelling on the road, leading to environmental impacts that may surpass those related to production and construction. While a comprehensive analysis should consider every phase of the pavement's life cycle, the absence of the use phase is not the only common omission found in pavement LCA studies.

The presence of uncertainty is an intrinsic feature of LCA. However, conventional LCA analyses often focus on single input and output values, which can significantly impact the reliability of the results. Although the need to address uncertainties in LCA has been long acknowledged, limited attention has been given to the development and inclusion of uncertainty analysis approaches in pavement LCA studies. This is particularly problematic in the early stages of PM, when information is limited, and uncertainty is high.

To address these limitations, this EngD project introduces the Environmental Performance Methodological Framework (EPMF), rooted in the LCA methodology and designed to overcome the common challenges of existing LCA frameworks from an early PM perspective. The EPMF guides the assessment of multiple types of M&R measures that are considered during network planning by the department of conservation of structure and maintenance of the RWS (ICO). Moreover, it incorporates various types and sources of uncertainty into the analysis, providing a more reliable platform for environmental assessments.

RESEARCH APPROACH

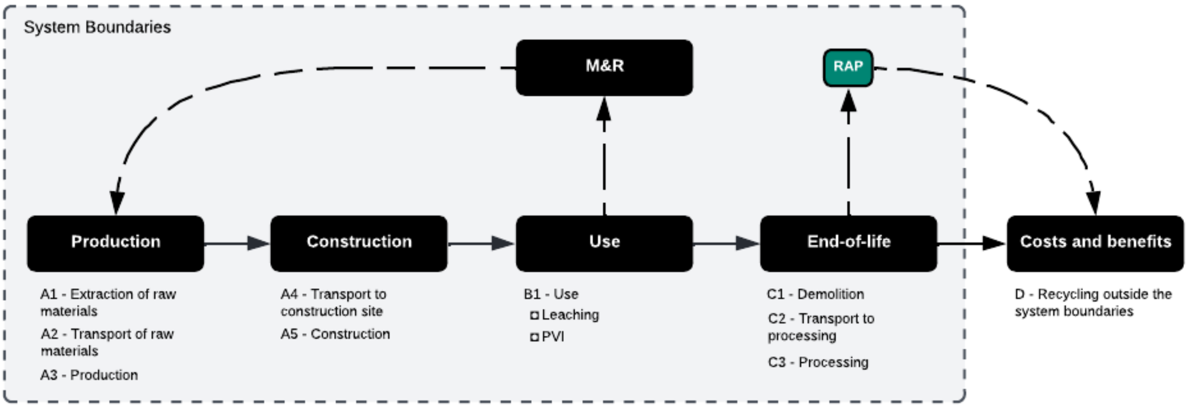
The EPMF was developed following the principles of the design science research methodology, which fosters the creation of effective interventions for real-world problems through an iterative and collaborative design process. The EPMF underwent multiple design cycles during the duration of the project aimed at refining and improving it, which was supported by insights gathered from user feedback and validation strategies.

The design process began with the development the problem investigation and the definition of the stakeholder requirements that direct the project (Chapters 1 and 2). Following, a literature review was conducted to collect information regarding ICO's context, the early stages of PM, and existing LCA and uncertainty methodologies (Chapters 3 and 4). The actual design of the EPMF (Chapter 5) consists of two main intertwined components: (1) the LCA framework module, aimed at evaluating the environmental impacts of pavement M&R, and (2) the uncertainty module, aimed at managing uncertainties within the LCA framework. The design was validated through systematic feedback, a case study, interviews, and a focus group (Chapter 6). Ensuing, key discussion points regarding the design and application of the EPMF, including generalizability insights and use specifications, are provided (Chapter 7). Finally, an extensive study on the further development and implementation of the EPMF in the RWS and ICO contexts was performed (Chapter 8). Under a multi-level perspective and the use of socio-technical transition pathway scenarios, this investigation places the framework into the broader, ongoing sustainability transition in the pavement sector.

THE EPMF

LCA FRAMEWORK DESIGN

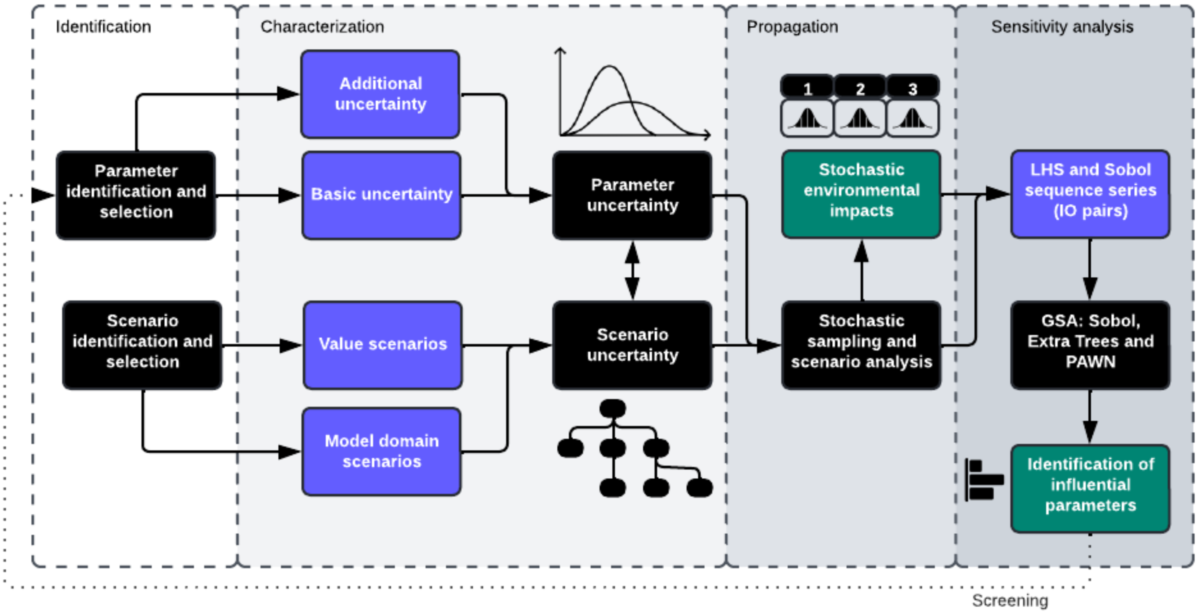
The LCA framework, illustrated below, covers multiple M&R treatments specific to the Dutch context, including different types of asphalt overlays, bituminous surface treatments (BST) and surface roughening techniques. It aligns with official Dutch reference documents, including the asphalt product category rules and the Determination Method.



The system boundaries of the analysis encompass all relevant life cycle processes and flows that are relevant for the analysis, ranging from production (material extraction, acquisition, transportation, and processing into asphalt mixtures) to construction (on-site paving activities and equipment use), use (with a focus on PVI), and end-of-life (EOL) (involving removal, recycling, and transportation of waste materials). To capture the effects of PVI, linear prediction models based on surface layer type and age were developed using measurements provided by the RWS. These models enabled the application of existing fuel consumption models to generate the use phase inputs needed to estimate PVI effects.

UNCERTAINTY FRAMEWORK DESIGN

The uncertainty framework, outlined below, is composed of four main steps: identification, characterization, propagation, and sensitivity analysis.



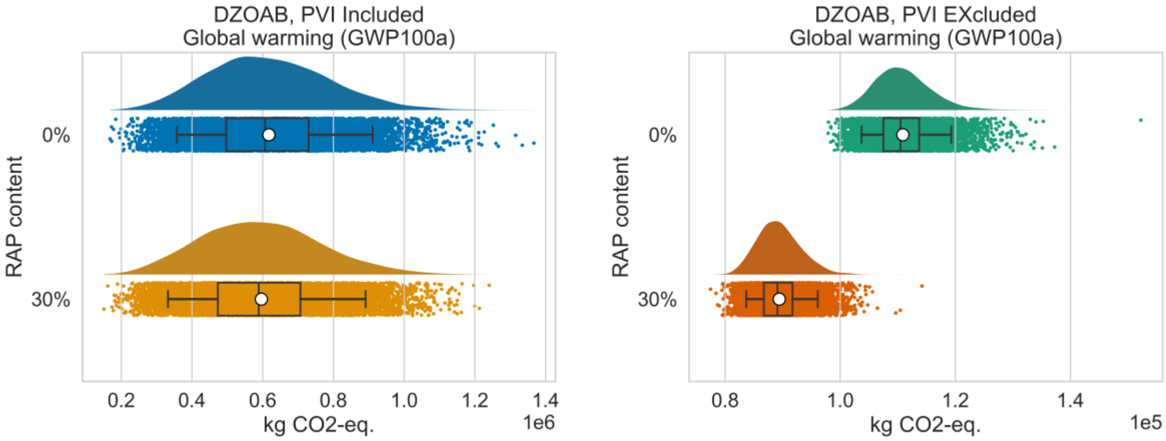
The first step involves identifying the uncertain input parameters and methodological choices that influence the environmental impact calculations. Parameter uncertainty is characterized using the ecoinvent method, a pedigree matrix approach widely employed in the pavement LCA scholarship, to account for uncertainty due to data quality and variability. It involves representing parameters as probability density functions (PDFs), capturing the range of possible values that inputs can take and their probabilities to do so. Methodological choices, on the other hand, such as variations in system boundaries or different value assumptions due to, say, different construction rates, are represented by different scenarios.

Once the uncertainties are characterized, they are propagated to the results using a combination of scenario analysis and stochastic sampling methods, specifically Latin-hypercube sampling (an efficient modification of Monte Carlo sampling) and Sobol sampling. These techniques effectively capture variations in uncertain parameters and scenarios, ensuring a thorough assessment of uncertainty.

Three global sensitivity analysis techniques—Extra Trees, Sobol, and PAWN—are used in the final step of the uncertainty analysis to measure the influence of the various input parameters on the overall output's uncertainty. These techniques evaluate the sensitivity of the results to variations across the entire input space, enabling the assessment of the relative significance of various inputs on the outcomes.

CASE STUDY RESULTS

The EPMF was applied to a case study involving a mill-and-fill treatment comprising a 50mm-thick overlay of Durable ZOAB (DZOAB) on a 1km-long road segment with 3 lanes over a 14-year lifespan. Two scenarios were examined: one with 0% reclaimed asphalt pavement (RAP) and another with 30% RAP content. Additional scenarios to examine the impact of excluding PVI effects from the analysis were also defined to get a better estimation of the sensitivity of the results.



The results, showcased above, underscore that even with relatively low PVI impact values, when the use phase is considered, impact reductions in other phases are nearly imperceptible. This emphasizes the need of incorporating the use phase and controlling pavement quality to mitigate extra fuel consumption attributed to increased RR, a topic that is often overlooked in the Dutch context.

The sensitivity analysis results further highlight the dominant role of PVI in driving uncertainty in the outputs when considering the use phase. This emphasizes the need for refined pavement performance and extra fuel consumption prediction models to reduce uncertainty and narrow down the range of environmental impact results, offering a more faithful representation.

When the use phase is excluded from the analysis, transportation processes and the import of aggregates from overseas are major contributors to the uncertainty in the results. These findings uncover key sources of uncertainty within the assessment, underlining areas where refined data and localized information can play a pivotal role in enhancing result accuracy.

FURTHER DEVELOPMENT AND IMPLEMENTATION

Three transition pathway scenarios exploring the potential futures of the EPMF and outlining its successful implementation within PM were devised. In each scenario, the EPMF seeks sustainability improvements in different ways.

The EPMF emerges either as an informative tool or a decision-support system with distinct requirements and implications. The results of this analysis indicate that, while the informative role aligns better with the current socio-technical landscape and regime, the decision-support role offers greater potential for advancing sustainability. However, the latter requires significant modifications to the way M&R plans are currently formulated and significant development and implementation efforts.

CONCLUSIONS

The EPMF delivers a platform for integrating environmental performance assessments into the early stages of PM. It achieves this by providing a structured framework for conducting LCAs on various M&R measures while taking uncertainties into account.

This framework guides the user through the various stages of the LCA methodology, from setting system boundaries and inventories, to interpreting and reporting the results. Notably, the EPMF stands out from conventional LCA-based approaches by incorporating an uncertainty analysis framework, making it a more reliable tool for PM decision-making, especially at the early stages when information is limited, and uncertainty is high. Furthermore, it includes the effects of PVI in the assessment, which account for a major fraction of the environmental impacts of the measures.

The results of this EngD project advance the applicability of LCA in the context of PM and improve our understanding of how uncertainties influence the outcomes of the analysis. Moreover, this project provides a strategic avenue for identifying areas with large potential for enhancing environmental performance. This involves estimating the extent to which impacts can be reduced, thereby transcending the conventional practice of solely focusing on identifying hotspots. By embracing this perspective, the project paves the way for more comprehensive and effective improvements in environmental performance within the PM domain.

TABLE OF CONTENTS

LIST OF TABLES, FIGURES AND EQUATIONS

TABLES

FIGURES

EQUATIONS

GLOSSARY

BST	Bituminous surface treatment
CMA	Cold-mix asphalt
DBFM	Design-build-finance-maintain
DSS	Decision-support system
EPMF	Environmental performance methodological framework
EOL	End-of-life
GPO	Department of large projects and maintenance of the RWS
GSA	Global sensitivity analysis
HMA	Hot mix asphalt
ICO	Department of conservation of structure and maintenance of the RWS (part of GPO)
IenW	Dutch Ministry of Infrastructure and Water Management
IPM	Integrated project management
IHP	Conservation plan
KES	Customer requirements specification
LCA	Life cycle assessment
LCCA	Life cycle costing analysis
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LHS	Latin hypercube sampling
LSA	Local sensitivity analysis
M&R	Maintenance and rehabilitation
MCDA	Multi-criteria decision analysis
MCS	Monte Carlo sampling
MDI	Mean decrease impurity
MJPV	Multi-year plan for pavement maintenance
MKI	Environmental cost indicator
MOO	Multi-objective optimization
NEN	Netherlands Normalization Institute
NMD	Nationale Milieu Database
NWSP	Network link plan
OBR	Object Management Regime (in Dutch: Object Beheerregimes)
PDF	Probability density function
PEM	Product Environmental Footprint
PIANOO	Expertise Center for Procurement of the Ministry of Economic Affairs and Climate
PIN	Performance indicator
PM	Pavement management
PMS	Pavement management system
POF	Project order form
PPO	Department of programs, projects and maintenance of the RWS

PPP	Public private partnership
PVI	Pavement-vehicle interaction
RAP	Reclaimed asphalt pavement
RB	Management Regime (in Dutch: Beheerregimes)
RBO	Reference Framework for Management and Maintenance (in Dutch: Referentiekader Beheer en Onderhoud)
RR	Rolling resistance
RUPS	Rijkswaterstaat Uniform Programming System
RWS	Executive organization from the IenW (in Dutch: Rijkswaterstaat)
SLA	Service Level Agreements
SRCC	Spearman rank correlation coefficients
TRL	Technology readiness level
VM	Variable maintenance
W&G	Roads and geotechnical engineering (part of GPO)
WM	Warm mix asphalt

1 INTRODUCTION

The maintenance and rehabilitation (M&R) of road pavements generate significant cumulative environmental impacts, motivating the pavement community to investigate more sustainable pavement management (PM) approaches. Road pavements are long-lived infrastructures that require the periodic application of M&R treatments to ensure that their condition does not deteriorate beyond undesirable values. However, each M&R cycle introduces a new source of environmental impacts due to the vast consumption of resources that they demand, including the depletion of natural resources, energy consumption, greenhouse gas emissions, and waste generation. As such, sustainability has been at the forefront of transportation agencies' agendas worldwide, and in turn, the need for incorporating environmental performance into the field of PM has ever more increased. Life cycle assessment (LCA) has emerged as an effective approach to do so that has become instrumental in the context of sustainability transition in PM (Miliutenko et al., 2014; Rangelov et al., 2020; Santero et al., 2011a, 2011b; Santos et al., 2015).

The use of LCA to evaluate environmental performance and inform decision-making across PM has become prevalent. LCA analyzes the environmental impacts of road pavements over the entire course of their service life including production, construction, use and end-of-life (EOL) (Santero et al., 2011a). It allows pavement managers to account for different environmental criteria in the development of M&R plans and projects, including the energy and resources required to carry out production and construction work, the emissions generated, and the effects of different materials and strategies. Different M&R treatments have different environmental impacts, and LCA helps pavement managers to understand them. However, the validity of LCA in this setting is often called into question, as most pavement LCA studies exclude important phases from the system boundaries of the analysis, particularly the use phase (Santero et al., 2011a), and ignore the effects of uncertainty resulting from various data sources and methodological choices in the results (Liu et al., 2022).

Conventional LCA studies often focus on the production, construction, and EOL phases of pavements, leaving the use phase out of their analysis (Xu et al., 2019). However, due to the effects of pavement-vehicle interaction (PVI), the environmental impacts of the use phase may account for a significant portion of total life cycle impacts (Akbarian et al., 2012; Gregory et al., 2016; Harvey et al., 2014, 2016; Noshadravan et al., 2013; Santos et al., 2022). PVI is the relationship between specific pavement characteristics and vehicle fuel efficiency, determined by pavement rolling resistance (RR). As RR increases, so do the fuel consumption and the emissions generated by the vehicles moving across the road (Bryce et al., 2014; Van Dam et al., 2015). In a comprehensive LCA analysis, it is essential to take into account every phase of the pavements' life cycle to ensure representativity and accuracy (Santero et al., 2011c), albeit the absence of the use phase is not the only omission often found in numerous pavement LCA studies.

The presence of uncertainty is an unavoidable factor in LCA studies. However, conventional LCA studies only look at single input and output values, which directly affects the reliability of the results. While recognizing the importance of uncertainty analysis in LCA (Huijbregts, 1998; Santero et al., 2011a), its development and integration into overall LCA research and applications have received limited attention (Bamber et al., 2020; Lo Piano & Benini, 2022). This is especially true in the pavement domain, where only a small number of studies that comprehensively incorporate uncertainty into LCA have been performed (Azarijafari et al., 2018; Bressi et al., 2022; Godoi Bizarro et al., 2020; Gregory et al., 2016; Huang et al., 2018; Noshadravan et al., 2013; Yu, Liu, et al., 2018; Zheng et al., 2020). Moreover, these studies do not offer clear guidance on how and when to integrate these approaches into PM, or the specific benefits and challenges that come along with doing so (Liu et al., 2022). While uncertainty is present along the entire PM cycle, its effects primarily manifest at the early planning stages, where information is scarce and uncertainty is high (Liljenström et al., 2020; Liu et al., 2022; Miliutenko et al., 2014). Paradoxically, it is precisely at this stage that significant opportunities to mitigate the environmental impacts associated with road construction projects are located (Miliutenko et al., 2014).

The early stages of PM are fraught with uncertainty since many M&R-related input parameters are either unknown or unclear due to limited data availability (Liljenström et al., 2020; Miliutenko et al., 2014). In light of these challenges, assessing environmental performance relies on multiple assumptions (Harvey et al., 2016; Liljenström et al., 2020), each of which introduces new sources of uncertainty to the analysis. While knowledge about the M&R projects increases as the PM process progresses, the ability to make changes to the treatment strategy becomes increasingly constrained (Miliutenko et al., 2014). Hence, LCA frameworks applied to the early PM planning stages should ideally accommodate uncertainty in the analysis (Liljenström et al., 2020).

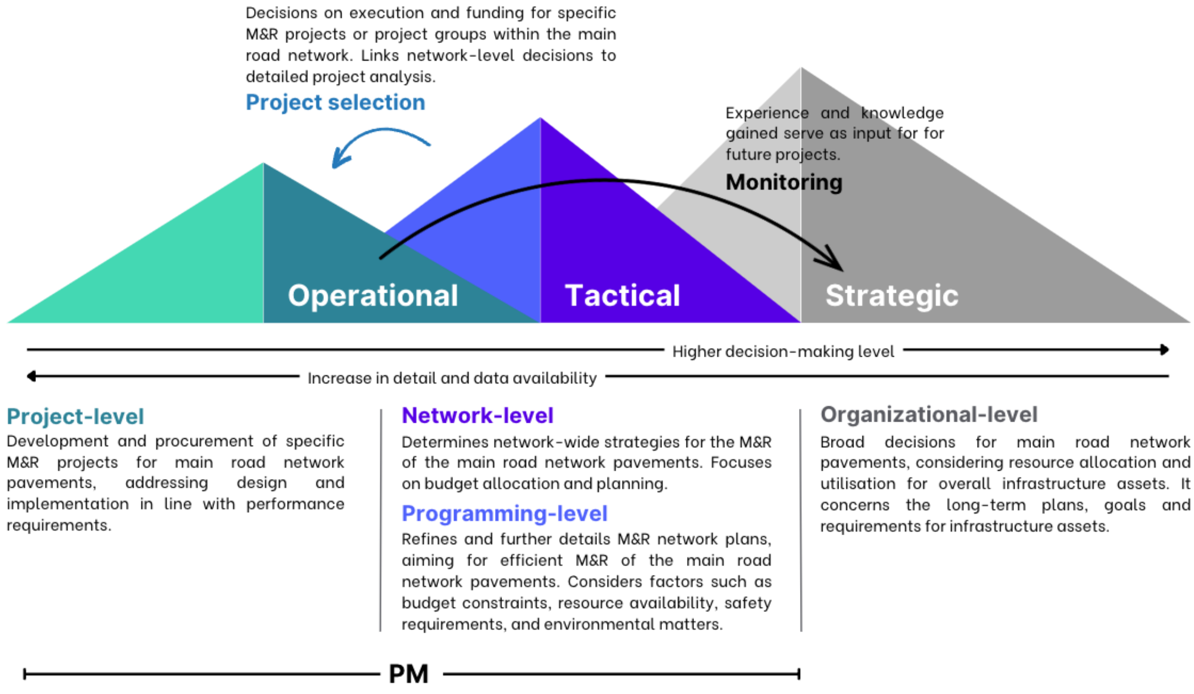
To improve the validity and applicability of LCA in PM, this EngD project report proposes a robust and comprehensive methodological framework known as the environmental performance methodological framework (EPMF). The goal of the EPMF is to evaluate the environmental performance of M&R strategies during the early stages of PM, when network-level plans are formulated. By considering various types and sources of uncertainty, the EPMF aims to provide reliable and accurate information regarding the environmental impact of M&R plans using LCA and uncertainty analysis techniques. The results of this project aim to promote more sustainable PM practices, emphasizing the importance of a comprehensive framework that encompasses all relevant life-cycle aspects, including pavement-vehicle interaction (PVI), and integrates uncertainty considerations in LCA studies to enhance their reliability, relevance, and representativeness.

1.1 PROBLEM CONTEXT

With a total length of 3,077 km of roads (Keijzer et al., 2015; Van der Pijl, 2022) and covering an area of 90 km2 of asphalt surfaces (Rijkswaterstaat, 2020), the Dutch main road network (Figure 1) is one of the busiest in Europe. It is under the management of the Rijkswaterstaat (RWS), the executive organization of the Dutch Ministry of Infrastructure and Water Management (IenW). The RWS is the agency responsible for the design, construction, management, and maintenance of the main highways and waterways in the Netherlands.

Figure 1. Main road network of the Netherlands.

In response to the urgent challenges caused by global warming and climate change, the RWS is actively pursuing ways to make infrastructure more sustainable (Rijksoverheid, 2020; Rijkswaterstaat, 2022a). This includes the asphalt pavement sector (Rijkswaterstaat, 2022b), which accounts roughly for one third of the RWS' CO2 emissions (Rijkswaterstaat, 2020). To achieve carbon neutrality by 2030 and satisfy Dutch climate targets, a shift towards more sustainable decision-making in PM (Figure 2) is essential.



Decisions on execution and funding for specific M&R projects or project groups within the main road network. Links network-level decisions to detailed project analysis.

Experience and knowledge gained serve as input for for future projects.

Development and procurement of specific M&R projects for main road network pavements, addressing design and implementation in line with performance requirements.

Determines network-wide strategies for the M&R of the main road network pavements. Focuses on budget allocation and planning.

Refines and further details M&R network plans, aiming for efficient M&R of the main road network pavements. Considers factors such as budget constraints, resource availability, safety requirements, and environmental matters.

Broad decisions for main road network pavements, considering resource allocation and utilisation for overall infrastructure assets. It concerns the long-term plans, goals and requirements for infrastructure assets.

Figure 2. RWS asset management decision-making levels with a focus on PM. Based on Flintsch & Bryant, (2006).

The sustainability transition pathway undertaken by the RWS (Rijkswaterstaat, 2022a, 2022b) poses a challenge for the Department of Conservation of Structure and Maintenance (ICO), which holds a key role in PM. As the nationwide branch of the RWS responsible for generating network-level M&R plans, internally known as the "Multi-Year Plan for Pavement Maintenance" (MJPV), ICO plays a crucial role in the early PM stages. The MJPV establishes the foundation for regional M&R plans and programming, project assignments, contracts, and procurement activities. However, sustainability has not been a guiding principle in its development, and no specific initiatives to include it therein have been undertaken.

Historically, ICO has relied solely on technical and cost principles to provide advice for M&R, leaving environmental criteria out of their scope. Economic analysis techniques, such as life cycle cost analysis (LCCA), and different pavement performance models are conventionally employed by transport agencies, including ICO, to support decision-making in PM (Harvey et al., 2014; Santos et al., 2018). However, as environmental concerns gain prominence, ICO faces the pressing challenge of incorporating environmental criteria into the network-planning of pavement M&R.

The first step in overcoming ICO's sustainability challenge is to gain a comprehensive understanding of the environmental performance of the M&R plans that they develop. While environmental performance assessments have been incorporated into the operations of other PM stages in the RWS, the context of ICO has not yet been explicitly addressed. To date, ICO has not integrated LCA or any other environmental assessment methodology into their practices The use of the RWS'S in-house LCA tool, DuboCalc, is limited to the project-level procurement stage (European Commission, 2013; Mentink et al., 2020; Miliutenko et al., 2014; Van Geldermalsen, 2020). Although few studies have been undertaken to investigate its applicability throughout the entire PM cycle (see Mentink et al., 2020), whether or not it is suitable for early M&R planning is still unclear. To enable a tailored and effective application of LCA within ICO's operations, a deeper understanding of what LCA studies in this context entail is needed. This includes the methodological choices involved, the required input parameters, the potential outcomes, and the influence of uncertainties in the analysis.

By deepening their understanding of LCA and its potential applications to their operations, ICO can cultivate a holistic and sustainable approach to PM. This will enable ICO to make meaningful contributions to the RWS's sustainability goals and navigate the transition pathway with success.

1.2 RESEARCH QUESTIONS AND OBJECTIVE

LCA is becoming the preferred approach for assessing environmental performance in PM, but its use within the RWS is currently limited to the project-level during procurement activities. While this practice is common among transportation agencies worldwide (Harvey et al., 2014), there is a need to expand the use of LCA to network planning and across the entire PM cycle to effectively support the sustainability transition in the pavement domain and maximize the value of the approach.

This EngD research project focuses on the early stages of PM, which is where ICO operates within the RWS. In this context, it is important to understand the specific aspects to consider when adopting LCA and ways to address the many uncertainties that arise at this stage. The main objective of this project is:

> *To design a comprehensive LCA-based methodological framework applicable to the early stages of PM that supports the effective evaluation and communication of the environmental performance of network-level M&R plans while considering different types and sources of uncertainty.*

A methodological framework serves as a structured and systematic approach that encompasses principles, guidelines, and procedures to accomplish a specific objective. It involves a series of steps that practitioners adhere to carry out their work and achieve the desired outcome. In this context, the goal is to enable the proper assessment of the environmental impacts of M&R during the early stages of PM.

Based on the objective, two main research question are derived:

1. *What are the key aspects to consider in the design of a comprehensive LCA framework employed to inform the environmental impacts of M&R in the early PM operations?*

2. *How can the LCA methodology account for multiple types and sources of uncertainty when assessing the environmental performance of M&R plans in the early PM operations?*

The answers to these questions provide knowledge that is required design an effective treatment to the research problem, the EPMF. The first question calls for a theoretical understanding of the system under analysis, i.e., pavement M&R, and the factors that influence the effectiveness of LCA in the context of PM. This includes how M&R should be defined in the context of LCA, which system boundaries must be considered (i.e., PVI), what are the specific data requirements for the analysis, and other important aspects. On the other hand, the second question claims knowledge on how to account for uncertainty in the LCA methodology. This requires a theoretical understanding of the different sources of uncertainty in LCA, as well as a conceptualization on how to integrate them into LCA studies. In accordance with the design science methodology (Wieringa, 2014), presented in the following section, the research questions posed and their corresponding answers serve as the knowledge foundation to fulfil the objective.

1.3 METHODOLOGY

Design science (Wieringa, 2014) is the research methodology employed in this project. It promotes the creation of robust, effective interventions to real-world problems through an iterative and collaborative design process. The methodology involves a series of iterative design cycles, with each cycle involving the refinement and improvement of the EPMF based on user feedback and evaluation.

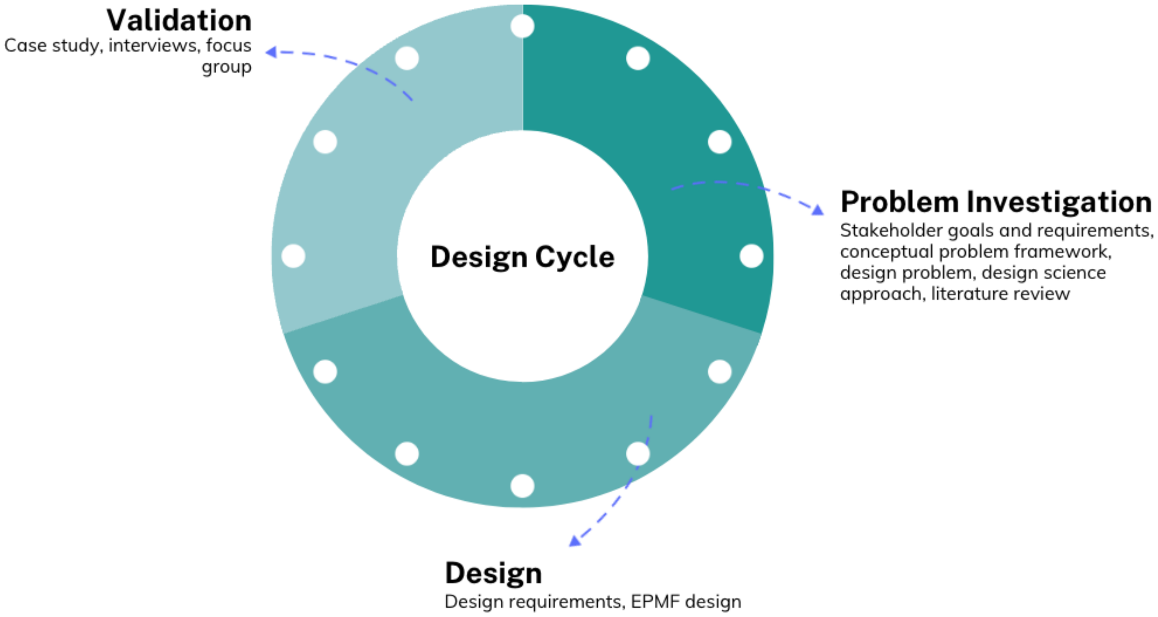


Figure 3. Design cycle in this project. Adapted from Wieringa (2014).

Each design cycle relies on three key steps: (1) problem investigation, (2) design, and (3) validation. To put in another way, the methodology involves systematically identifying and investigating the problem context, designing a solution, and providing evidence about the effectiveness of the solution. Figure 3 schematizes the design cycle application in the context of this research.

In this project, the problem context is the early stages of the PM operations, specifically the context of ICO, where there is a need for a tailored LCA framework that accounts for multiple sources of uncertainty and limited information. The design outcome is the EPMF, a methodological framework envisioned to bridge the gap between theory and practice, enabling a sustainability transition in the early-stage PM operations. Finally, the design is validated by means of a case study, interviews, and a focus group. Chapter 2 discusses design science and its application for this project in further detail.

1.4 DELIVERABLES

The main design outcome of this project is the EPMF, the methodological framework presented in this report. To validate the EPMF, and facilitate its use and further implementation, an accompanying digital application that embodies its design is provided. This application provides users with a working interface to input, access and create data, making it easier to integrate the EPMF into the PM operations of ICO. It is important to note that the EPMF itself, as articulated in this document, is the most crucial deliverable of this project, with the digital application being just one of several possible demonstrations of the EPMF.

Additionally, two conference proceedings papers were developed as part of this project:

- 'A Life Cycle Assessment Framework for Pavement Maintenance and Rehabilitation Considering Uncertainties' was presented at the 8th International Symposium on Life-Cycle Civil Engineering (IALCCE 2023) in Politecnico Di Milano in Milan, Italy on the 4th of July of 2023. The conference proceedings can be found using the following reference:

  Biondini, F., & Frangopol, D.M. (Eds.). (2023). Life-Cycle of Structures and Infrastructure Systems: PROCEEDINGS OF THE EIGHTH INTERNATIONAL SYMPOSIUM ON LIFE-CYCLE CIVIL ENGINEERING (IALCCE 2023), 2-6 JULY, 2023, POLITECNICO DI MILANO, MILAN, ITALY (1st ed.). CRC Press. https://doi.org/10.1201/9781003323020

- ‘Dissecting uncertainty in life cycle assessment studies for sustainable pavement management’ has been submitted to the 8th Eurasphalt and Eurobitume (E&E) Congress set to take place in Budapest, Hungary on the 19-21 of June 2024, and is awaiting acceptance.

Furthermore, an online presentation titled ‘Dissecting Uncertainty in Life Cycle Assessment Studies for Pavement Management: A Comparative Study of Tree Ensemble Methods, Distribution-Based and Variance-Based Global Sensitivity Analysis’ was given on March 29th of 2023 as part as the ‘Data Science for Pavement Symposium’ (DSPS) webinar week hosted by the Federal Highway Administration, the Missouri Center for Transportation, and the University of New Hampshire.

The IALCCE conference paper and the abstract preceding the online DSPS presentation are included at the end of this document for reference. However, the E&E conference paper cannot be shared with the public at this time.

1.5 OUTLINE OF THE REPORT

The outline of the report conforms to the design science standards. Chapter 1 provides and introduction to the project. Chapter 2 outlines the conceptual problem framework and provides background information on design science, as well as how it is executed in this project. The next two chapters present theoretical and practical information that establish the knowledge base of the project. Chapter 3 explores the topic of PM in the Netherlands, zooming into the role of ICO therein, as well as key aspects of their work. Chapter 4 investigates the role of LCA in the PM context, including fundamental information of the LCA of pavements, uncertainty analysis in LCA, and the specific role that LCA plays in the Dutch PM context. Thereafter, the design profile of the main EPMF components is delivered in Chapter 5. Note that early design iterations used for the case studies are not presented as a chapter. Chapter 6 follows with the design validation activities performed in this project, a case study to test and verify the design, as well as the application and results of interviews and a focus group. Chapter 7 comments on the final version of the EPMF and consolidates its design by providing use specifications and addressing its generalizability. Chapter 8 covers potential courses of action for the development and implementation of the EPMF as part of the broader transition to sustainable road pavements, describing elements of its socio-technical context and exploring its maturity. At last, the final conclusions and recommendations of this project are presented in Chapter 9.

2 A DESIGN SCIENCE APPROACH

This chapter details the conceptual problem framework of the project and the design science methodology application that guides the research. The conceptual problem framework focuses on understanding the problem's nature, context, and structure. Chapter 1 introduces the project and, by extension, the conceptual problem framework. This chapter goes deeper into the subject and builds up to the definition of the design problem and the approach to address it, which can be found at the end of this chapter. To do so, this chapter describes in detail the steps involved in the design science methodology in the context of the project, namely the problem investigation, design, and validation, and the methods used to carry out each step.

In the problem investigation, the problem context is further investigated as preparation for the design activities of the EPMF. The conceptual problem framework plays a critical role in the problem investigation phase of the design science methodology. It provides a clear understanding of the problem being addressed and helps to guide the development of a treatment. In this project, the conceptual problem framework identifies the need for a solution that can integrate environmental performance into the early stages of PM. It also highlights the limitations of current PM approaches, which often prioritize cost and performance over environmental impact. This creates a need for a EPMF that can provide pavement managers with the necessary information to consider environmental impacts alongside other factors. Overall, the conceptual problem framework provides a clear understanding of the problem being addressed and helps to guide the design tasks. Thereafter, a literature review is conducted to gather information about the early stages of PM in the context of ICO, and about existing LCA and uncertainty methodologies. The outcomes of the literature review increases the understanding of the context and provide a sound and scientific foundation for the design of the EPMF.

In the design phase, the EPMF components are presented: the LCA framework module and the uncertainty module. The LCA framework serves as the basis for the evaluation of the environmental impacts of pavement M&R, while the uncertainty framework helps to manage the uncertainties in the LCA framework.

Finally, the validation phase checked whether the EPMF met the design requirements and assessed its value in relation to its context. To do this, feedback was solicited from users and experts, and improvements were made to the system based on their feedback. Validation was conducted via systematic feedback processes, a case study, interviews, and a focus group.

The ultimate goal of this project is to develop a methodological framework for more sustainable PM that can be operationalized by ICO. Its implementation, however, is not within the scope of the project, albeit a roadmap addressing its future development and implementation is provided into this document. The roadmap aims to guide ICO in the process of integrating the EPMF into their PM operations and maximize its potential.

Following, the stakeholder goals and requirements, as well as the design scope, boundaries, architecture, and problem are described.

2.1 STAKEHOLDER GOALS

The success of the project is determined by the extent to which the stakeholder goals are met. This section answers the question *what are the stakeholder goals and requirements for the EPMF to properly function on ICO's early stages of PM?* To do so, the first step was to conduct a stakeholder analysis that considers the individuals or groups who can affect or be affected by the project. ICO is the primary stakeholder, as they are both the client driving the design and development of the EPMF and the ultimate user of the final product. Meanwhile, the University of Twente (UT) is responsible for the EPMF's development. Other stakeholders are also included in the analysis, to provide insights into the socio-technical context to which the EPMF belongs.

The Onion Model (Alexander, 2005) is used to organize stakeholders based on their hierarchical levels in the system (i.e., the EngD project or EPMF) and to describe their goals and interests (see Table 1). The identification of the goals facilitates a clear understanding of the problem being addressed and helps to guide the development of the design requirements. By ranking the stakeholders in such a way, the project aims to effectively design a EPMF that meets the primary users' needs while taking into account the broader socio-technical context of implementation.

Table 1. Stakeholders' goals.

Class	Stakeholder	Goals
System: early PM stages.	ICO *(client)*	As the main client and user of the research, ICO's primary goal is to have a reliable and applicable EPMF that improves their PM operations, with a particular focus on sustainability. Their goals include extending the current M&R plans from cost to environmental indicators, determining the environmental impacts of different types of pavements, gaining insight into the uncertainties behind the environmental impacts of M&R, and being advised on how to include the environmental impacts of road pavement M&R into their plans without changing the current decision-making process. Additionally, they aim to adhere to the RWS pool of knowledge and resources if it is deemed pertinent for the context.
	UT	The main goal of the university in this project is to develop a useful and effective EPMF for ICO, which can potentially be generalizable, while also advancing knowledge in the field of sustainable PM. The university may also have an interest in publishing research papers and securing funding for future projects based on the success of this one.
Containing system: Dutch PM cycle	RWS	As the parent organization of ICO, RWS is interested in ensuring that the PM operations are carried out effectively and efficiently to guarantee good road infrastructure, and with minimal environmental impact to meet their sustainability goals. They may also have goals related to budgeting and resource allocation across the organization.
	Contractors	The main goal of contractors is to submit competitive bids and get awarded contracts, which in turn requires them to keep the environmental impacts related to their bids as low as possible. Thereafter, they wish to carry out PM works effectively, within budget and timeframe, while adhering to the contract terms. They may also have a vested interest in reducing costs and keeping and/or improving their reputation with the RWS.
Wider environment: Dutch main road network	Road users	The primary goal of road users is to have safe and well-maintained roads that allow for efficient transportation. They may also have an interest in minimizing disruptions and environmental impact during the M&R process.

The project primarily focuses on meeting the goals of ICO, the main client and user of the EPMF, whose operations fall into the early PM stages. UT, the party in charge of its development, has its own goals, which are balanced against those of ICO.

As the parent organization of ICO, the RWS's broader goals are also explored and addressed in a set of specific design considerations, as well as in the development and implementation plans. This is rooted in the fact that ICO is not the only RWS unit active in PM; numerous other actors also participate. This may eventually lead to the adoption of a unified approach to evaluate the environmental performance of pavements across the organization. Such a prospect would effectively position the EPMF within the wider context of PM and have an impact on its overall applicability and functionality. In order to respond to these challenges and ultimately prevent obsolescence, it is important to factor in such a possibility wherever practical.

The contractors and the road users are included in the analysis to portray other actors with a stake in PM and the M&R of road pavements. This provides insights on the possible influence of the projects beyond its immediate context of use.

2.2 STAKEHOLDER REQUIREMENTS

The stakeholder requirements that guide the design of the EPMF are derived from the stakeholder goals and presented in Table 2. Input from ICO was gathered through systematic meetings and feedback sessions, resulting in a set of agreed-upon requirements for the design of the EPMF. This approach aims to ensure the EPMF is effective, feasible, and meets the needs of the stakeholders.

Table 2. EPMF stakeholder requirements.

Requirement	Description
Applicability	The EPMF should be applicable to a comprehensive range of M&R measures and pavement types to ensure its usefulness and effectiveness for ICO and the M&R planning for the Dutch main road network.
Completeness	The EPMF will be based on a comprehensive LCA methodology that covers all the important aspects associated with M&R in the context of ICO.
Representativeness	The EPMF will use consistent, up-to-date, appropriate data to ensure that the environmental impacts associated with different M&R measures are accurately assessed in the context of ICO.
Reliability	The EPMF will be trustable by its user and will include an appropriate uncertainty analysis methodology to ensure that the results are reliable.
Clarity / transparency	The EPMF will be transparent and easy to understand, presenting clear and concise information. It will also provide a clear explanation of its methodology and assumptions to enable stakeholders to understand and employ its outcomes.
Flexibility	The EPMF will be flexible, allowing for the incorporation of future changes or additions, without compromising its functionality.
Relevance	The EPMF will be functional. It will provide relevant and actionable information that can be used by ICO to improve M&R plans and support more sustainable decisions.
Compatibility	The EPMF should be compatible with ICO's current tools, specifically IVON2, and its output should serve as input for the EPMF.
Integration	The EPMF should integrate the knowledge and tools already used by RWS, such as DuboCalc, provided their suitability for the EPMF.
Complementarity	The EPMF should complement ICO's current decision-making process without changing it and offer additional criteria for assessing the suitability of M&R plans.
Scientific soundness	The methodological approach and insights obtained by the EPMF should be based on the literature on LCA, uncertainty analysis and sustainable PM, and further contribute to it.

2.3 DESIGN SCOPE

The focus of the project is on incorporating environmental performance into the early PM stages, particularly when network plans are developed and ICO operates. Figure 4 provides a focused perspective on the scope of the project, beginning with the broader sustainability ambitions of the RWS and narrowing down to ICO's specific sustainability goals. The figure highlights the role of the EPMF within ICO's context, aligning with the RWS's overarching sustainability ambitions. As ICO operations serve as an initial stage in the larger PM process within the RWS organization, which is currently seeking to make infrastructure more sustainable, advancements towards more sustainable practices at a smaller scale propagate upwards throughout the organizational chain.

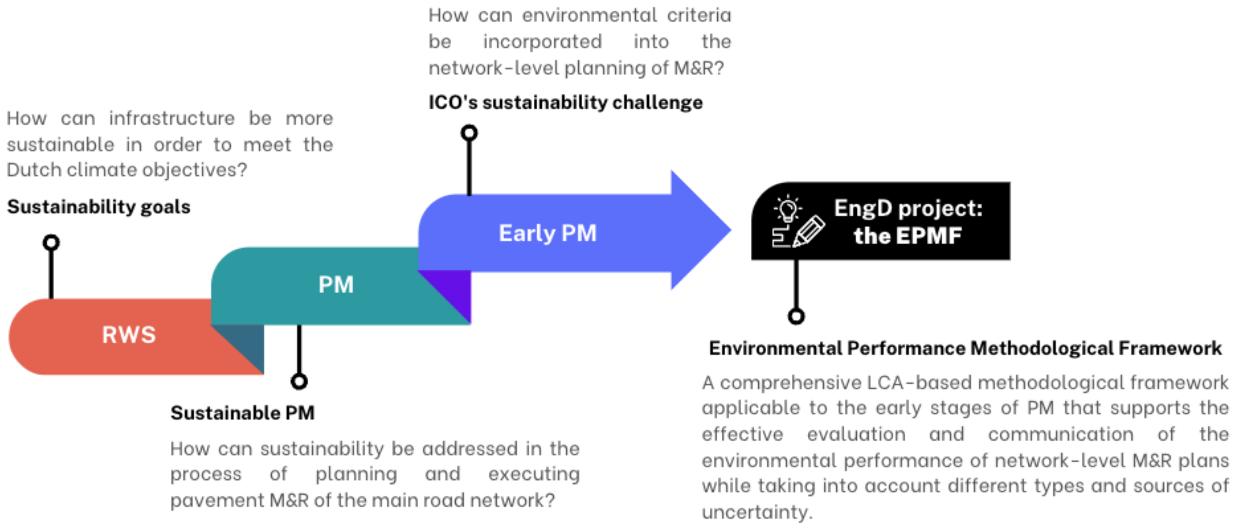


Figure 4. Scope of the EngD project.

2.4 DESIGN BOUNDARIES

To define the design space of the EPMF, specific boundaries and conditions were established in accordance with the project scope. These boundaries are relative to the immediate context of use: ICO's operations.

- The EPMF is limited to the road pavements managed by the RWS. Road pavements outside the main road network of the Netherlands are, in principle, outside the scope of the EPMF.
- The EPMF is tailored to the early PM stages where ICO operates and network-level M&R plans are developed. Previous and subsequent PM stages are, in principle, outside the EPMF design scope.
- The EPMF targets the MJPV, which serves as a network-level M&R plan directing the execution of a collection of M&R measures. Other M&R plans are, in principle, outside of the EPMF scope.
- The EPMF only considers the M&R treatments include in the M&R measures that can be instructed by the MJPV. Other M&R treatments are, in principle, outside the EPMF scope.

2.5 DESIGN ARCHITECTURE

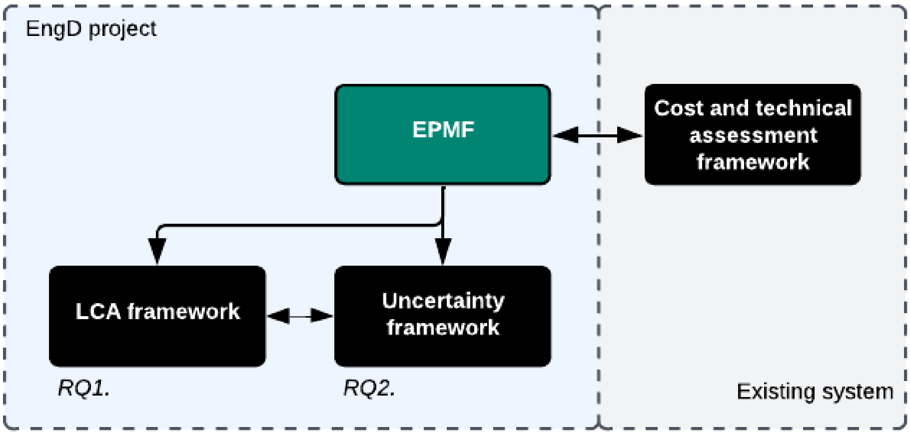


Figure 5. EPMF architecture.

Based on the research objective and stakeholder goals and requirements, the EPMF is composed of two main components or modules, an LCA framework and an uncertainty framework. These components have a certain degree of interaction, as the uncertainty framework depends on output obtained via the LCA framework and vice versa. The LCA framework embodies research question 1, whereas the uncertainty framework does so for research question 2.

In addition to the LCA and uncertainty frameworks, the EPMF will interact with the existing cost and technical assessment framework employed by ICO, following the requirements of compatibility, integration, and complementarity. The basic EPMF design architecture is portrayed in Figure 5.

2.6 DESIGN PROBLEM AND STRATEGY

The design problem in the context of this project refers to the problem that is being addressed by the design of the EPMF. Put into the design problem form (Wieringa, 2014), the design problem that governs this research is:

> *Improve sustainability at the early stages of PM;*
> *By designing an LCA-based methodological framework for network-level M&R plans that accounts for uncertainties;*
> *And satisfies the stakeholder goals and requirements;*
> *So that ICO incorporates environmental performance into their operations.*

The design problem can now be reframed as a design question or technical research problem/question (Wieringa, 2014):

> *How to design an LCA-based methodological framework for network-level M&R plans that accounts for uncertainties and satisfies the stakeholder goals and requirements, so that ICO incorporates environmental performance into their operations, to improve sustainability at the early stages of PM?*

To develop a satisfactory design, certain questions related to the development of knowledge that is relevant, valid, and useful for the problem context are in place. In design science, these questions are known as ‘knowledge questions’ and they guide the research process. In this project, knowledge questions help to ensure that the resulting EPMF is grounded in sound theoretical and practical knowledge and meets the needs and goals of the stakeholders. In other words, knowledge questions drive the creation of the EPMF and ensure that it is effective in addressing the problem context. The knowledge questions that target the design problem are:

PROBLEM INVESTIGATION

1. *What are the stakeholder goals and requirements for the EPMF to properly function on ICO's early stages of PM?*
2. *What does M&R of the main road network in the context of ICO entails?*
3. *What are the key aspects that needs to be considered in a pavement M&R LCA?*
4. *What are the key sources of uncertainty in pavement LCA, and how do they affect decision-making in the early stages of PM?*
5. *What are the most common and effective methods for quantifying and managing uncertainty in LCA?*
6. *What are the limitations and challenges of using LCA and uncertainty analysis for decision-making in the early stages of PM?*

DESIGN

1. *What are the key components and functionalities of an LCA-based EPMF that can effectively address the stakeholder goals and requirements and incorporate uncertainty?*

2. *How can the LCA-based EPMF be designed to facilitate usability and integration into ICO's existing operations and decision-making processes?*
3. *How can the LCA methodology be tailored to assess pavement M&R in the early stages of PM?*
4. *How can different sources of uncertainty be incorporated into the EPMF to provide a comprehensive and accurate representation of environmental performance in the early stages of PM?*

VALIDATION

1. *How can the EPMF be validated to ensure that it produces the intended outcomes and meets the stakeholder goals and requirements?*
2. *What are appropriate strategies for evaluating the effectiveness of the EPMF on ICO's environmental performance in the early stages of PM?*
3. *How can the EPMF be refined and improved based on validation feedback results to better serve the stakeholder goals and requirements?*

The answers to these knowledge questions can be found throughout this document in their respective sections. Figure 6 schematizes the adoption of the design science approach in this project in relation to the structure of the document.

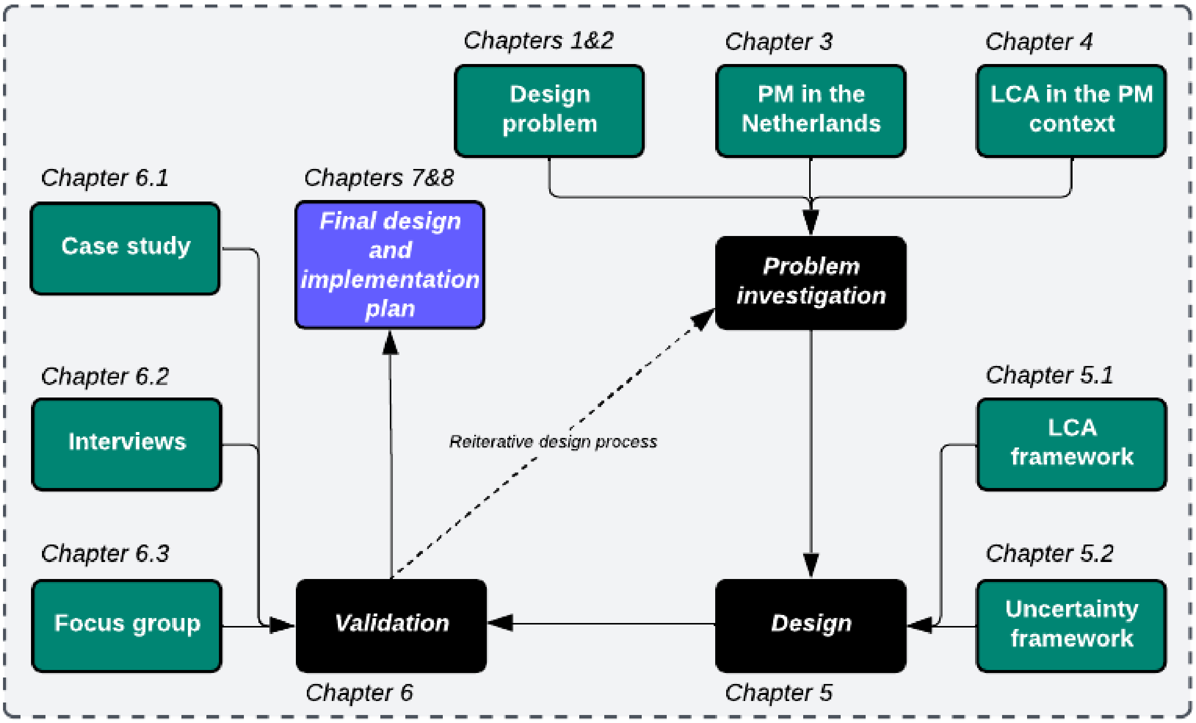


Figure 6. Design science methodology approach for the development of the EPMF. Black boxes represent the main steps in design science, green boxes depict the themes of each step, and the purple boxes stand for the final products of this project.

The transfer to the problem context or, in other words, the real-world implementation of the design in its context of use, is not compulsory in the design science methodology. Thus, embedding the EPMF in the context of ICO is not part of the scope of the EngD project. However, Chapter 8 covers the future development and implementation of the framework, proposing several courses of action to develop and implement the EPMF within the PM cycle, and laying the foundation for the further deployments of the EPMF in the operations of ICO.

3 PM IN THE NETHERLANDS

In the Netherlands, PM of the main road network refers to the systematic process of planning and executing M&R works carried out every year to guarantee that the pavements of the main road network remain in good condition and ensure their safe and efficient operation. M&R in this context is applied to asphalt pavements and is divided into regular and variable maintenance (VM). On the one hand, regular maintenance consists of small activities to preserve pavements, such as weeds control, pavements cleaning, and preventive local sealing[1]. VM, on the other hand, is condition dependent and comprises a broad range of measures, from bituminous surface treatments (BST) to extend pavements' lifespan, to hot mix asphalt (HMA) overlays to restore pavement condition. PM herein refers to the strategy that is followed to plan and execute VM. All the stages and steps of the PM process of the main Dutch network are hereby referred to as the Dutch PM cycle.

This chapter provides an overview of the Dutch PM cycle. It describes what VM of the main road network entails and how it is carried out, providing insights into the specific M&R measures considered and their characteristics. It ultimately answers to the question of *what does M&R of the main road network in the context of ICO entails?*

3.1 THE DUTCH PM CYCLE

The Dutch PM cycle is a systematic, intricate process that involves several stakeholders; from the road authorities who inspect the roads, establish network- and project level plans, and procure the M&R works, to the contractors who submit bids, get awarded projects, and execute M&R works. In the Netherlands, the main road network is managed by the RWS. Within the RWS, there are several smaller departments that play different roles in the PM process. ICO is a key actor involved in the early PM stages and plays a framework-setting role in M&R. Under cost-technical criteria, ICO generates a network-level plan that addresses which sections require M&R, what treatments should be applied, and when. Table 3 provides an overview of the entire Dutch PM cycle and the participation of ICO therein.

Table 3. Steps of the Dutch PM cycle (Van der Pijl, 2022).

Stage	Description	Actors involved
Road inspections	The condition assessment of road pavements is conducted through detailed road inspections. These inspections entail a combination of on-site assessments and desk studies to accurately map the extent of damages and gather information about the surface characteristics of the main state roads and highways. By conducting these assessments, potential risks and vulnerabilities are identified. The identified risks are then translated into risk management measures, which are developed to safeguard the long-term functionality and performance of the road network. These measures are designed to mitigate the impact of identified risks and ensure the continuous and reliable operation of the network.	Inspection Directive ´Het Inspectiehuis´; external service providers
Network-level planning: *Preparation of the MJPV*	The MJPV serves as a network-level M&R plan for the main road network, providing guidance on the VM M&R measures that are needed to guarantee that the pavements of the main road network remain in good condition and ensure their safe and efficient operation. These measures are determined based on the condition of the network, which is assessed through road inspections. The MJPV specifies what, when, and where M&R activities should be carried out, along with the associated costs. It considers the projected condition of the pavements in the next five years, allowing for proactive planning of M&R efforts.	RWS: ICO

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[1] For more information regarding regular maintenance refer to Van der Pijl (2020).

Stage	Description	Actors involved
	It is important to note that the MJPV does not provide project-level advice. The M&R measures included in the plan are indicative and subject to revision and improvement throughout the PM cycle as needed. The MJPV is integrated into the RWS Uniform Programming System (RUPS) for strategic purposes. To support the development of the MJPV, the software IVON2 is used, assisting in the elaboration of the plan. Overall, the MJPV plays a crucial role in guiding the M&R activities at a network level, taking into consideration the predicted condition of the pavements and providing a tactical roadmap for the VM of the road network	
Programming: *MJPV revision and regional plans*	The programming tasks are decentralized to the regional level, where each region develops its own programming based on conservation plans known as Infrastructure Maintenance Plans (IHPs). These plans are created in alignment with the MJPV. During this stage, network link plans (NWSP) are also consulted to ensure a smooth transition between the RWS's overall asset management strategic and tactical levels. At this stage, if necessary, a directive may be issued to modify the MJPV and save the changes in the RUPS. Regional offices may seek technical guidance from ICO when updating the MJPV and IHPs. The final programming is determined by considering factors such as budget constraints, resource availability, safety requirements, and environmental considerations. It involves the detailed specification of the M&R measures, including the treatment final definition, milling depths, overlay thicknesses, as well as their location and scheduling for execution. By incorporating these considerations and guidelines, the final programming ensures that the appropriate M&R measures are defined and implemented to address the VM needs of the road network regions while accounting for fixed constraints and requirements.	RWS: regions, network link team, ICO.
Execution I: *Project-level assignments and procurement*	During this stage, the programming process progresses to project-level assignments known as project order forms (POFs). The POFs group together the M&R measures based on their location and the year of intervention. Once the POFs are finalized, they are transformed into contracts to facilitate the execution of the M&R services. The M&R services specified in the contracts are translated into performance-based indicators, which are used as criteria for selecting the contractors through a tender process. In this step, additional customer requirement specifications (KES) may be incorporated to ensure that the contractor meets specific customer expectations. After the tender process, the M&R projects are awarded to the contractor who submits the most favorable proposal. A performance-based contract is thereafter drafted, outlining the functional requirements that the road pavements indicated in the contract must meet over a defined period. Unlike traditional contracts that provide detailed specifications for the M&R measures, performance-based contracts focus on the desired outcomes and performance targets to be achieved. By adopting performance-based contracts, the RWS aims to promote innovation and efficiency in the execution of M&R projects, allowing contractors the flexibility to choose the most suitable methods and techniques to achieve the desired performance outcomes	RWS: regions, IPM team [a], PPO [b]; Contractors
Execution II: *Design and implementation of M&R projects*	During this stage, the contractor begins the implementation of the M&R measures specified in the contract. The contractor is responsible for determining the specific M&R measures to be applied, considering the functional requirements outlined in the contract. They are also in charge of managing and executing the M&R project.	Contractors; RWS

Stage	Description	Actors involved
Monitoring: *performance supervision*	Throughout the implementation process, the performance of the M&R measures is closely monitored and verified. The RWS ensures that the contractor adheres to the proposed plans and meets the required standards and specifications. This monitoring and verification process helps to assess the effectiveness and quality of the implemented M&R measures. By monitoring and verifying the performance of the implementation, the RWS can identify any deviations from the proposed plans and take corrective actions if necessary. This ensures that the M&R project stays on track and that the desired outcomes are achieved. It also serves as a mean to evaluate the contractor's performance and compliance with the contractual obligations.	RWS

Notes:
[a] Integrated project management (IPM) teams manage large infrastructure projects within the RWS.
[b] Procurement activities are conducted within the Programs, Projects and Maintenance (PPO) branch of the RWS.

3.1.1 THE EARLY PM STAGES: ICO AND THE PREPARATION OF THE MJPV

Every year, ICO produces a new version of the MJPV, a M&R plan at the network-level for the VM of the main road network, following the directives stipulated in the Object Management Regime (OBR) for road pavements (Van der Pijl, 2022). The OBRs are specifications that outline the M&R activities carried out by RWS and define the necessary measures for sustaining and ensuring the proper functioning of the national infrastructure networks. These regimes profile the average annual costs associated with infrastructure management, i.e., PM, at a national level over the long term. Together with the Management Regimes (BRs), they serve as the basis for the Reference Framework for Management and Maintenance (RBO), which provides a comprehensive overview of the networks' coherence, associated costs, and budget considerations. The RBO is applied in budget preparation and multi-year agreements between RWS and the IenW regarding performance, resource allocation, and associated risks, as well as for the development of service level agreements (SLAs), and the annual management plan, while also incorporating relevant developments that may impact future M&R costs Van der Pijl, 2022).

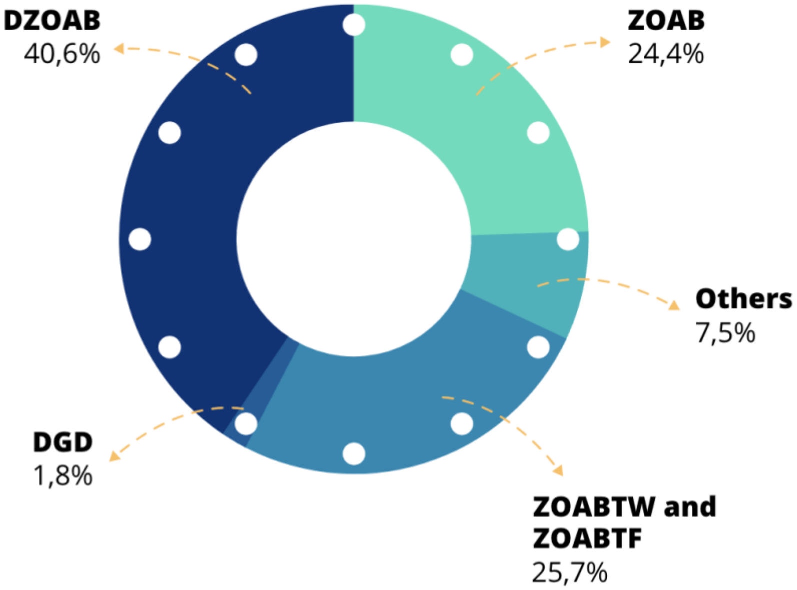

Figure 7. Percentual distribution of surface layer asphalt coatings. Retrieved from Van der Pijl, (2022).

The MJPV covers the entirety of the main road network pavements (excluding entrances, exits, and roads to service areas), from which approximately 92.5% of the surface area corresponds to porous asphalt surfaces (ZOAB layers). Figure 7 illustrates the distribution of asphalt surface coatings over the main road network. VM is of predictive character: it is condition dependent and performed upon reaching intervention levels (Sánchez-Silva & Klutke, 2016; Van der Pijl, 2022).

The MJPV sets a M&R strategy for the following seven years. The decision-making process involves in its developments is primarily based on performance assessments, considering factors like pavement quality and surface distresses. These assessments inform the scheduling and selection of specific M&R measures that are deemed necessary for the targeted road segments. By analyzing pavement condition and identifying distresses, ICO can determine the appropriate timing and types of M&R interventions required for optimal road performance.

The M&R measures outlined in the MJPV provide an early indication of the treatments needed in the main road network, but they should not be regarded as project-level advice. The final definition of the M&R plans occurs during the later stages of the PM cycle, wherein the MJPV and the M&R measures that it prescribes serve as foundation for regional programming and project-level assignments.

3.1.1.1 IVON2

The preparation of the MJPV is assisted by the RWS pavement management system (PMS) software IVON2 (long-term planning system for pavement maintenance), which serves as a long-term planning system for pavement M&R. IVON2 leverages cost and technical assessment models to determine the M&R treatments that are needed, their locations, as well as their scheduling based on the current and future condition of the network pavements. Furthermore, after the M&R strategy is set and the costs are calculated, IVON2 generates a financial multi-year budget for strategic planning purposes.

While IVON2 delivers the costs associated with the M&R plans it generates, it does not directly integrate life-cycle cost optimization in the selection of M&R treatments for single years or a multi-year horizon. In practice, PMS do not often perform life-cycle cost optimizations directly (Harvey et al., 2014). Instead, IVON2 employs optimization techniques, based on optimal M&R strategies implemented within the software, using decision trees that instruct specific actions when specific criteria are met, i.e., the most cost-efficient M&R measure for specific network state situation (Van der Pijl, 2022). When relevant, the next major M&R cycle date estimate is also considered in the analysis. This exercise results in enhanced network plans that consider the timing and prioritization of interventions based on segment-specific M&R needs and anticipated application times. This approach aims to minimize costs and nuisances by strategically combining, accelerating and/or delaying interventions as required.

The identification of specific treatment locations and budget constraints can be addressed in later stages of the PM process, where additional constrained optimization techniques can be employed to prioritize treatments based on the available budget (Harvey et al., 2014).. This enables the allocation of resources based on strategic considerations.

3.1.1.2 THE ARCHITECTURE OF THE MJPV

Both graphical and tabular representations of the M&R plan are included in the MJPV. These representations, depicted in Figure 8 and Figure 9, provide different but essential information for a comprehensive understanding of the M&R network plan.

The graphical representation in Figure 8 offers a visual depiction of the carriageway road segments where M&R activities will be implemented and the corresponding year of intervention. It also highlights normative damages or pavement features that have reached specific thresholds. By presenting a top view of the road's carriageway, it indicates the number of lanes at different points and the type of surface layer currently in place. Additionally, it includes the date of the most recent surface layer replacement, providing valuable insights into the historical maintenance activities.

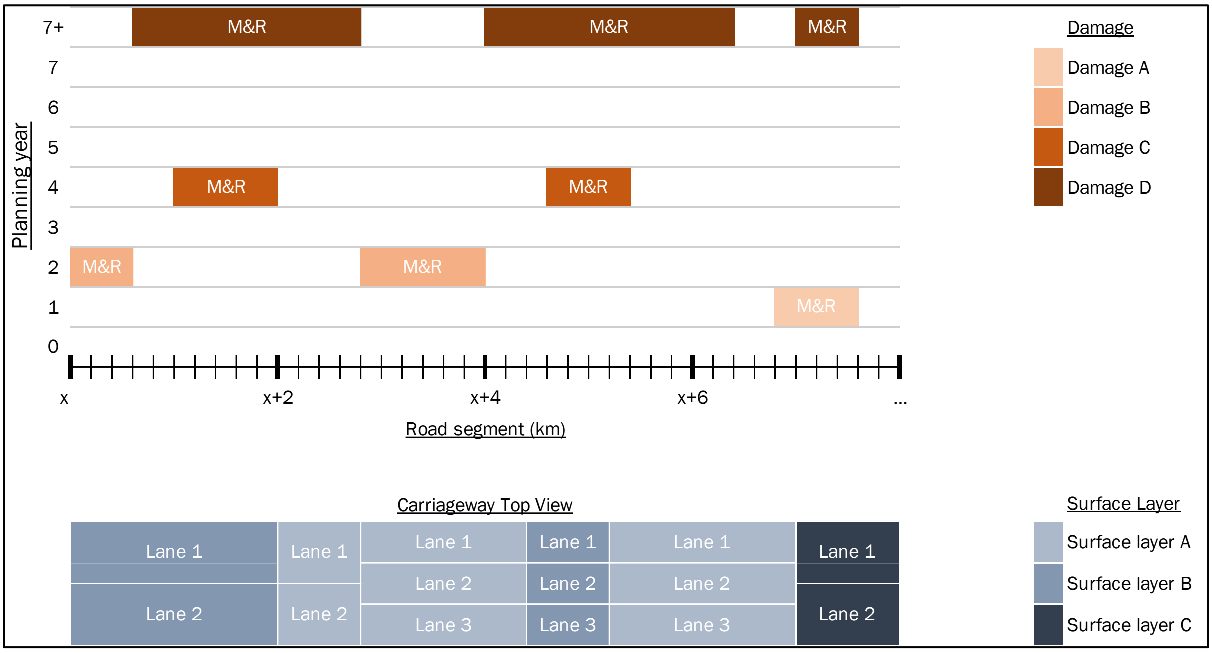

Figure 8. Graphical representation of the MJPV. Some aspects of the representation that are not relevant here have been excluded from the representation for clarity. Year 0 indicates the present year. X indicates the kilometer number of the road visualized.

On the other hand, the tabular representation in Figure 9 provides a detailed breakdown of each carriageway road segment that will undergo M&R in the upcoming years. Each row represents a road segment that is at least 200 meters long and provides important information related to that segment. The columns in the table include the location of the road segment, the lanes involved in the treatment (e.g., right or left lanes), the total surface area of the road segment to be addressed by the M&R measure, the scheduled year for the M&R intervention, the normative damage or pavement feature that triggers the need for the M&R measure, information about the binder layer if it is part of the coverage, the specific M&R measure to be applied, and the corresponding VM category to which the M&R measure belongs. This tabular format allows for a comprehensive understanding of the specific characteristics and requirements associated with each road segment.

Both formats complement each other, providing a complete and detailed picture of the MJPV. They enable PM actors to effectively plan and manage M&R activities by understanding the reference location, timing, and specific requirements of each intervention.

Road segment (100m)	Description	Surface area	Planning year	Normative damage / feature	Binder layer information	M&R measure	LEM / MM
Segment A							
Segment B							
Segment C							
				…			
Segment N							

Figure 9. MJPV in the form of tables. A few columns, which provide information that is not relevant here, have been excluded from the representation for clarity.

3.2 M&R MEASURES

M&R is applied to asphalt pavements structures[2] to delay deterioration or reset their condition. Its primary objective is to delay deterioration and enhance the overall performance of the pavements by addressing existing damages and preventing further degradation. VM measures are specifically designed to target the surface and binder layers[3] before the onset of extensive and severe damage to the pavement structure that exceed acceptable thresholds[4].

VM measures address a wide range of pavement damages and features that can significantly impact the pavement structure. These include rutting, longitudinal unevenness or roughness, skid resistance, transverse gradient, load bearing capacity, cracking, fatigue cracking, and raveling. By targeting these specific issues, VM measures effectively improve the overall condition of the pavement and ensure its long-term performance.

This chapter provides valuable insights into the various M&R measures recognized under VM and that are applicable in the context of the MJPV. These measures are categorized based on their classification as either maintenance or rehabilitation treatments, as well as the specific VM strategy they target. Furthermore, the chapter presents detailed descriptions of each measure's treatment approach, highlighting their unique characteristics and applicability.

3.2.1 MAINTENANCE VS. REHABILITATION

ICO incorporates various M&R measures into their plans for VM. These measures can be categorized as either rehabilitation measures or maintenance measures, depending on the type of treatment they entail. Rehabilitation measures primarily focus on restorative treatments, while maintenance measures aim to improve the condition of pavement surface.

Rehabilitation measures within this context involve the application of functional and structural HMA overlays[5], with and without reclaimed asphalt pavement (RAP) contents, to replace worn or deteriorated asphalt layers and mitigate further pavement degradation. Functional overlays specifically target the surface layer, while structural overlays encompass the replacement of both the surface and binder layers. These rehabilitation measures effectively restore functionality and reset the lifespan of the layers intervened.

Maintenance measures, instead, encompass treatments other than HMA overlays and primarily aim to preserve the surface layer, ensuring its good condition and delaying deterioration. These treatments include bituminous surface treatments (BST) and surface roughening techniques, though the use of

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[2] Pavement structure refers to the main structure of a road, which is composed by different asphalt layers that in turn are composed by different asphalt mixtures or pavement materials.

[3] The surface layer is found at the top and provides the course in immediate contact with the vehicles. The binder layer, also referred to as interlayer, is the intermediate course found between the surface and base layers.

[4] To learn more about the severity and extent thresholds for the damages to the road pavements, refer to Van der Pijl (2020).

[5] Some authors allocate functional asphalt overlays within the category of pavement maintenance as they do not significantly increase structural capacity (Chowdhury, 2011; Izeppi et al., 2015; Torres-Machí et al., 2018; Wu et al., 2010). However, in this context, both functional and structural overlays are allocated within the category of pavement rehabilitation due to its implementation similarities following the classification provided by Alberta Infrastructure and Transportation (2006).

rejuvenators[6] is gradually becoming more prevalent. By implementing these maintenance measures, the RWS can effectively maintain the quality and prolong the service life of the pavement.

3.2.2 HOW ARE THE MEASURES CLASSIFIED?

To differentiate between different M&R approaches, the RWS classifies M&R measures them into two main VM categories: major maintenance (MM)[7] and life-extending maintenance (LEM) (Van der Pijl, 2022). Figure 10 provides an overview of these VM classes.

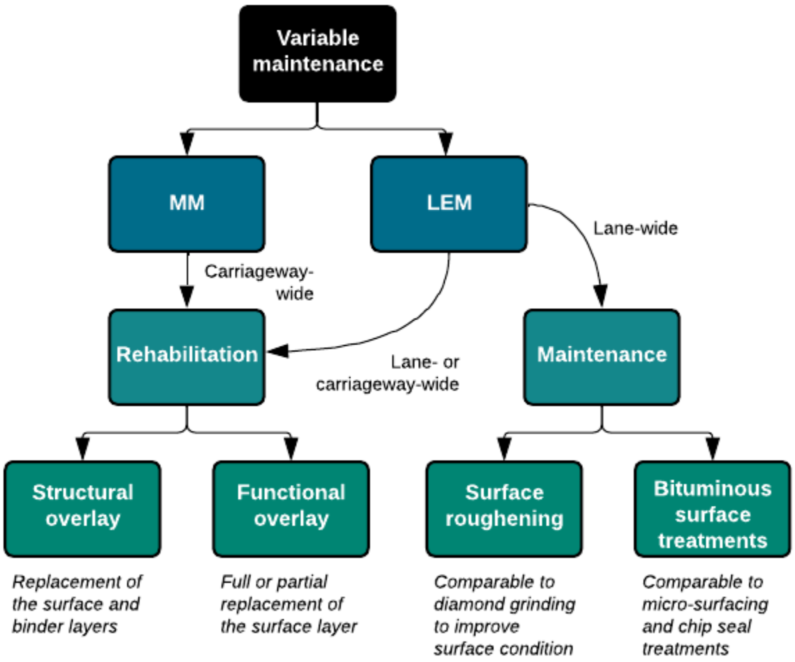

Figure 10. Overview of variable maintenance types and treatments.

MM involves carriageway-wide rehabilitation measures that focus on replacing the surface layer of the road, including all lanes and shoulders in one direction of travel. Additionally, if necessary, MM may also involve the replacement of the binder layers at the end of their expected service life. In the past, binder layers were typically replaced every two rehabilitation cycles, or every second time the surface layer was replaced. Now, ICO recommends that the binder layer is replaced every MM cycle (Van der Pijl, 2022).

LEM aims to ensure that the entire carriageway reaches its intended service life before MM is applied. It implements a variety of M&R measures that can be carried out carriageway-wide or lane-wide. LEM is commonly applied to the right-side lane of the carriageway, as it tends to deteriorate faster due to higher traffic volumes. By performing M&R more frequently on the right side, the condition of the pavements in that lane is restored before the service life of the carriageway ends. As time passes, the left-side lanes will eventually start showing damage for the first time, while the right-side lane will also begin to deteriorate again. This synchronized deterioration indicates that the intended service life of the

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[6] Maintenance measures may also include the application of rejuvenators to sections with asphalt pavements that are five years old (Van der Pijl, 2022). On average, 2500 sections of 100 m are eligible each year. Rejuvenators deliver a life extension of 3 years in average. However, as rejuvenators are not yet part of the asphalt measures included in the asphalt norms book of the RWS (GPO, 2022), they lie outside of the VM scope defined in this project.

[7] MM in the context of VM shouldn't be confused with the classification of major and minor maintenance that is sometimes employed by the FHWA (see Wu, Groeger, et al., 2010).

carriageway is approaching, suggesting that it is time to implement MM, always applied carriageway-wide[8] (Boumanm & Hooimeijer, 2005; Hooimeijer, 2001; Van der Pijl, 2022).

3.2.3 MEASURES OVERVIEW: TREATMENTS AND APPLICABILITY

Within the VM framework, a diverse range of maintenance and rehabilitation (M&R) measures are implemented to ensure the longevity and functionality of the pavement network. Rehabilitation measures, applicable to both LEM and MM approaches, involve the use of HMA overlay treatments on the pavements. Table 4 provides an overview of the pavement systems (asphalt mixtures/layers) targeted by rehabilitation measures, while Figure 10 further breaks down the applicability of these measures to these systems.

Table 4. Asphalt layers of the road pavements of the Dutch main road network (GPO, 2022; Van der Pijl, 2022).

Layer type	Asphalt layer (Dutch abbreviation)	Asphalt layer (English name)	Composition: official Dutch asphalt mixture	Common layer thickness (mm)	RAP content (%)[1]	Number of measures
Surface Layers	AC Surf	Asphalt concrete for surface layer	AC 16 Surf (DAB), AC 11 Surf	40-50	30	15
	ZOAB	Porous asphalt	ZOAB 16	50	0	12
	DZOAB	Sustainable porous asphalt	DZOAB 16	50	25	9
	ZOABTW	Two-layer porous asphalt	Composed by 25mm of 2L-ZOAB 8 (top-layer) over 45mm of 2L-ZOAB 16 (bottom layer)	70	25 (bottom layer)	11
	ZOABTF	Two-layer fine porous asphalt	Composed by 20mm of 2L-ZOAB 5 (top-layer) over 50 mm of 2L-ZOAB 16 (bottom-layer)	70	25 (bottom layer)	10
	SMA	Stone mastic asphalt or stone matrix asphalt	SMA-NL 11	35	0	6
	DGD	Thin silent asphalt	Variable	30	0	10
	ZOABDI	Porous asphalt with thin lamination additions	ZOAB 8	25	0	2
Binder layers	AC Bind	Asphalt concrete for binder layer	AC 22 Bind (OAB), AC 22 Bind (STAB)	50-100[2]	60	29

Notes: DAB = Dense asphalt concrete, OAB = Open asphalt concrete, STAB = Crushed stone asphalt concrete.

[1] The RAP content is indicative; it is based on assumptions made by the RWS for cost purposes and does not necessarily reflect the actual RAP content that a mixture may contain.

[2] The thickness of the binder layer is determine by structural calculations. It's common practice to specify binder layer replacements in structural overlays at the MJPV at either 50mm or 100mm thick.

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[8] A typical rehabilitation strategy for roads with three or more lanes plus hard shoulder involves rehabilitating the adjacent traffic lane, i.e., the lane next to the right-side lane, after four years from the rehabilitation of the right-side lane and before MM is carried out (Boumanm & Hooimeijer, 2005).

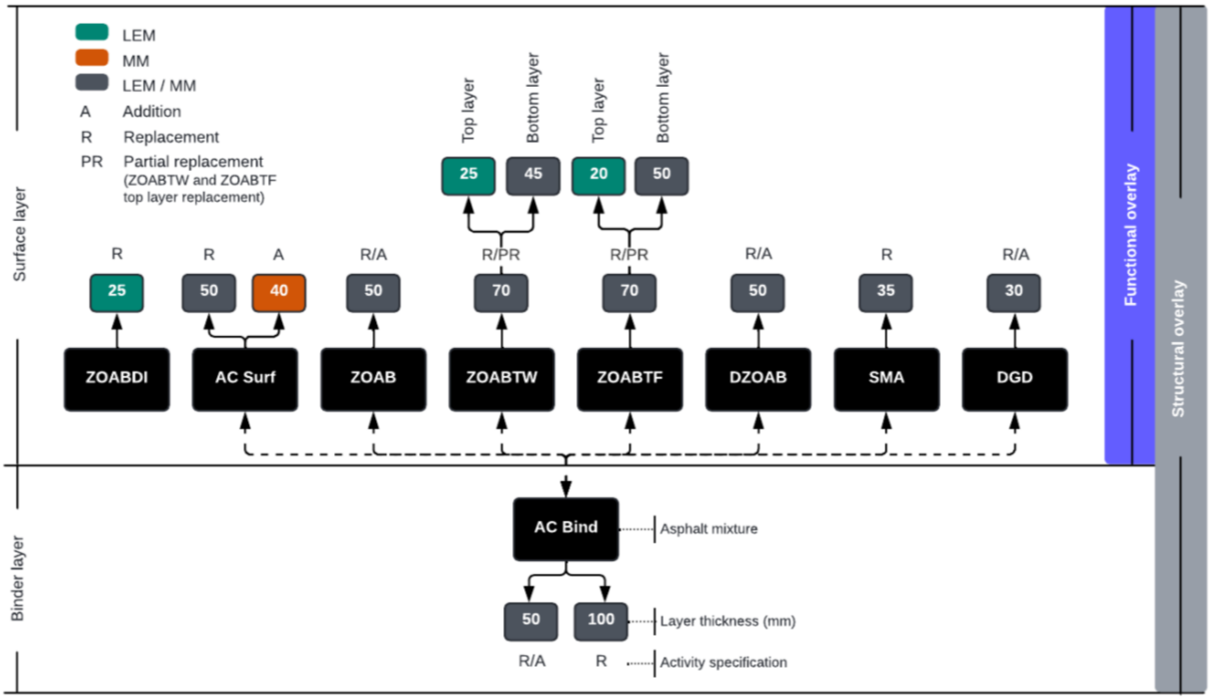

Figure 11. Rehabilitation measures breakdown.

In contrast, maintenance measures exclusively fall under the LEM strategy and focus solely on the surface layer, typically applied lane-wide. LEM measures encompass two categories: bituminous surface treatments (BST) and surface roughening treatments. Figure 12 breaks down the different maintenance measures and their applicability.

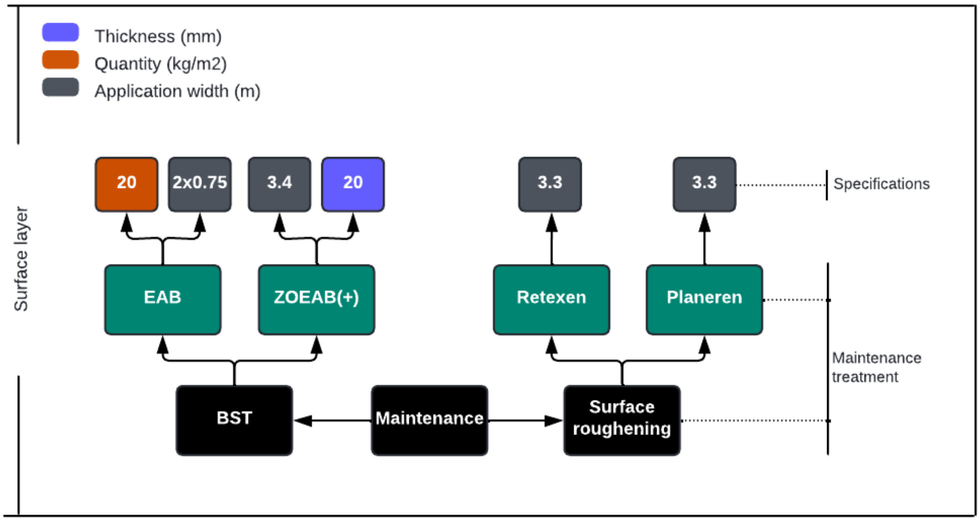

Figure 12. Maintenance measures breakdown.

BSTs encompass the application of asphalt emulsions, namely ZOEAB and EAB, to treat raveling and rutting. ZOEAB and EAB are a cold-mix mixture of bitumen emulsion, cement, water and mineral aggregates (CROW, 2016; Van der Kruk et al., 2022) . ZOEAB is employed to treat ravelling and is suitable for porous asphalt surfaces (e.g., ZOAB) and DGD surfaces, whereas EAB is used to treat rutting and preserve dense asphalt layers (e.g., AC Surf and SMA). ZOEAB(+), is a variant of ZOEAB that requires the application of an adhesive layer made of bitumen emulsion plus rejuvenator (the + layer) followed by a thin layer of ZOEAB (CROW, 2016; Kneepkens et al., 2019).

Surface roughening treatments are another type of maintenance measures aim to improve the micro and macrotexture of the surface asphalt layers with the use of a specialized machine (e.g., Unimog machine) to upgrade the surface condition. Two types of surface roughening treatments are distinguished: 'retexen' for densely graded asphalt surfaces, and 'planeren' for porous asphalt surfaces. They are both comparable to the more commonly known diamond grinding asphalt treatment.

Table 5 and Table 6 give full information on each M&R measure that can be implemented by ICO in the MJPV as part of VM, providing a comprehensive overview of all M&R measures including their specific characteristics.

Table 5. Maintenance measures (GPO, 2022).

Type	Treatment type	RWS Code	Measure width		Description
			Type	Application width (m)	
LEM	Bituminous surface treatment	QAN0110	L	2x0.75	Micro-surfacing: restoration of wheel path (2x0.75m) (longitudinal rut repair) with 20mm (theoretical thickness) of Emulsieasfaltbeton (EAB)
		QAN0111	L	3.4	Chip seal: raveling correction with 20kg/m2 Zeer Open Emulsieasfaltbeton (ZOEAB)
	Surface roughening	QAN0145	L	3.3	'Retexen' for AC Surf and SMA surface layers
		QAN0146	L	3.3	'Planeren' for ZOAB and other porous asphalts surface layers

Notes: L = lane.

Table 6. Rehabilitation measures (GPO, 2022).

Type	RWS Code	Surface layer mixture	Measure width		Overlay characteristics			Description
			Type	Application width (m)	Type	Layers out (#)	Layers in (#)	
LEM	QAN0104	AC Surf	L	4	F	1	1	50mm AC Surf out / in
	QAN0105	AC Surf	L	5	F	1	1	50mm AC Surf out / in
	QAN0106	AC Surf	L	4.5	S	2	2	50mm AC Surf out - 50mm AC Bind out/in - 50mm AC Surf in
	QAN0107	AC Surf	L	5	S	2	2	50mm AC Surf out - 50mm AC Bind out/in - 50mm AC Surf in
	QAN0108	AC Surf	L	4.5	S	3	3	50mm AC Surf out - 50+50mm AC Bind out/in - 50mm AC Surf in
	QAN0109	AC Surf	L	5	S	3	3	50mm AC Surf out - 50+50mm AC Bind out/in - 50mm AC Surf in
	QAN0129	ZOAB	L	4	F	1	1	50mm ZOAB out/in
	QAN0130	ZOAB	L	5	F	1	1	50mm ZOAB out/in
	QAN0131	ZOAB	L	4.5	S	2	2	50mm ZOAB out - 50mm AC Bind out/in - 50mm ZOAB in
	QAN0132	ZOAB	L	5	S	2	2	50mm ZOAB out - 50mm AC Bind out/in - 50mm ZOAB in
	QAN0133	ZOAB	L	4.5	S	3	3	50mm ZOAB out - 50+50mm AC Bind out/in - 50mm ZOAB in
	QAN0134	ZOAB	L	5	S	3	3	50mm ZOAB out - 50+50mm AC Bind out/in - 50mm ZOAB in
	QAN0139	DZOAB	L	4	F	1	1	50mm DZOAB out/in

	QAN0140	DZOAB	L	5	F	1	1	50mm DZOAB out/in
	QAN0101	ZOABTW	L	4	F	1	1	70mm ZOABTW out/in
	QAN0102	ZOABTW	L	4.5	S	2	2	70mm ZOABTW out - 50mm AC Bind out/in - 70mm ZOABTW in
	QAN0103	ZOABTW	L	4.5	S	3	3	70mm ZOABTW out - 50+50mm AC Bind out/in - 70mm ZOABTW in
	QAN0116	ZOABTW	L	4	F	1	1	Top layer 25mm 2L-ZOAB8 out/in
	QAN0117	ZOABTW	L	5	F	1	1	Top layer 25mm 2L-ZOAB8 out/in
	QAN0150	ZOABTF	L	4	F	1	1	Top layer 20mm 2L-ZOAB5 out/in
	QAN0151	ZOABTF	L	4.5	S	3	3	70mm ZOABTW out - 50+50mm AC Bind out/in - 70mm ZOABTF in
	QAN0112	SMA	L	4	F	1	1	35mm SMA-NL out/in
	QAN0113	SMA	L	5	F	1	1	35mm SMA-NL out/in
	QAN0114	SMA	L	4.5	S	2	2	35mm SMA-NL out - 50mm AC Bind out/in - 35mm SMA-NL in
	QAN0115	SMA	L	5	S	2	2	35mm SMA-NL out - 50mm AC Bind out/in - 35mm SMA-NL in
	QAN0120	DGD	L	4.5	S	2	2	30mm DGD out - 50mm AC Bind out/in - 30mm DGD in
	QAN0121	DGD	L	5	S	2	2	30mm DGD out - 50mm AC Bind out/in - 30mm DGD in
	QAN0124	DGD	L	4	F	1	1	30mm DGD out/in
	QAN0125	DGD	L	5	F	1	1	30mm DGD out/in
	QAN0126	DGD	L	4.5	S	3	3	30mm DGD out - 50+50mm AC Bind out/in - 30mm DGD in
	QAN0127	DGD	L	5	S	3	3	30mm DGD out - 50+50mm AC Bind out/in - 30mm DGD in
	QAN0148	ZOABDI	L	4	F	1	1	25mm ZOAB out - 25mm ZOABDI in
	QAN0149	ZOABDI	L	5	F	1	1	25mm ZOAB out - 25mm ZOABDI in
	QAN0201	ZOABTW	C	3.5 x #L +S	S	2	2	70mm ZOABTW out - 50mm AC Bind out/in - 70mm ZOABTW in
	QAN0202	AC Surf	C	3.5 x #L +S	F	1	1	50mm AC Surf out/in
	QAN0203	DGD	C	3.5 x #L +S	S	2	2	30mm DGD out - 50mm AC Bind out/in - 30mm DGD in
	QAN0204	ZOAB	C	3.5 x #L +S	S	2	2	50mm ZOAB out - 50mm AC Bind out/in - 50mm ZOAB in
	QAN0205	DZOAB	C	3.5 x #L +S	S	2	2	50mm DZOAB out - 50mm AC Bind out/in - 50mm DZOAB in
	QAN0206	ZOABTF	C	3.5 x #L +S	S	2	2	70mm ZOABTF out - 50mm AC Bind out/in - 70mm ZOABTF in
MM	QAN0301	ZOABTW	C	3.5 x #L +S	F	1	1	70 ZOABTW out/in
	QAN0302	ZOABTW	C	3.5 x #L +S	S	2	2	70 ZOABTW out - 50 AC Bind out/in - 70 ZOABTW in
	QAN0303	ZOABTW	C	3.5 x #L +S	F	1	2	70 ZOABTW out - 50 AC Bind in - 70 ZOABTW in
	QAN0343	ZOABTW	C	3.5 x #L +S	F	1	1	50 ZOAB out - 70 ZOABTW in
	QAN0344	ZOABTW	C	3.5 x #L +S	F	1	1	50 DZOAB out - 70 ZOABTW in
	QAN0341	ZOABTF	C	3.5 x #L +S	F	1	1	70 ZOABTF out/in
	QAN0350	ZOABTF	C	3.5 x #L +S	F	1	1	50 ZOAB out - 70 ZOABTF in
	QAN0351	ZOABTF	C	3.5 x #L +S	F	1	1	50 DZOAB out - 70 ZOABTF in
	QAN0352	ZOABTF	C	3.5 x #L +S	F	1	1	50 AC Surf out - 70 ZOABTF in

QAN0353	ZOABTF	C	3.5 x #L +S	F	1	1	50 Other out - 70 ZOABTF in
QAN0354	ZOABTF	C	3.5 x #L +S	F	1	1	70 ZOABTW out - 70 ZOABTF in
QAN0355	ZOABTF	C	3.5 x #L +S	S	2	2	70 ZOABTW out - 50 AC Bind out/in - 70 ZOABTF in
QAN0304	AC Surf	C	3.5 x #L +S	F	1	1	50 AC Surf out/in
QAN0306	AC Surf	C	3.5 x #L +S	S	2	2	50 AC Surf out - 50 AC Bind out/in - 50 AC Surf in
QAN0307	AC Surf	C	3.5 x #L +S	F	1	2	50 AC Surf out - 50 AC Bind in - 50 AC Surf in
QAN0308	AC Surf	C	3.5 x #L +S	F	0	1	40 AC Surf overlayer
QAN0310	AC Surf	C	3.5 x #L +S	F	1	1	30 DGD out - 40 AC Surf in
QAN0312	AC Surf	C	3.5 x #L +S	F	1	1	50 ZOAB out - 40 AC Surf in
QAN0314	AC Surf	C	3.5 x #L +S	F	1	1	70 ZOABTW out - 40 AC Surf in
QAN0315	AC Surf	C	3.5 x #L +S	F	1	1	70 ZOABTF out - 50 AC Surf in
QAN0319	SMA-NL11	C	3.5 x #L +S	F	1	1	35 SMA-NL out/in
QAN0321	SMA-NL	C	3.5 x #L +S	S	2	2	35 SMA-NL out - 50 AC Bind out/in - 35 SMA-NL in
QAN0338	DGD	C	3.5 x #L +S	F	1	1	30 DGD out/in
QAN0345	DGD	C	3.5 x #L +S	F	1	1	50 ZOAB out - 50 AC Bind in - 30 DGD in
QAN0336	DGD	C	3.5 x #L +S	F	0	1	30 DGD overlayer
QAN0325	ZOAB	C	3.5 x #L +S	F	1	1	50 ZOAB out/in
QAN0327	ZOAB	C	3.5 x #L +S	S	2	2	50 ZOAB out - 50 AC Bind out/in - 50 ZOAB in
QAN0328	ZOAB	C	3.5 x #L +S	F	1	1	50 ZOAB out - 50 AC Bind in - 50 ZOAB in
QAN0329	ZOAB	C	3.5 x #L +S	F	0	1	50 ZOAB overlayer
QAN0330	ZOAB	C	3.5 x #L +S	S	3	3	50 ZOAB out - 100+50 AC Bind out/in - 50 ZOAB in
QAN0331	DZOAB	C	3.5 x #L +S	F	1	1	50 ZOAB out - 50 DZOAB in
QAN0333	DZOAB	C	3.5 x #L +S	S	2	2	50 DZOAB out - 50 AC Bind out/in - 50 DZOAB in
QAN0337	DZOAB	C	3.5 x #L +S	F	1	1	30 DGD out - 50 DZOAB in
QAN0339	DZOAB	C	3.5 x #L +S	F	0	1	50 DZOAB overlayer
QAN0340	DZOAB	C	3.5 x #L +S	F	1	1	40 AC Surf out - 50 DZOAB in
QAN0349	DZOAB	C	3.5 x #L +S	F	1	1	50 AC Surf out - 50 DZOAB in

Notes: C = carriageway; L = lane; NA = not applicable; F = functional; S = structural. Lane application width indicates the width of the surface layer replaced in lane-wide LEM. Roads with two lanes + hard shoulder have a lane-width of 5m and road with three lanes or more + hard shoulder have a lane width of either 4 or 4.5m. The width of 4m applies to a functional overlay. The width of 4.5m applies to structural overlays due to the serrations required for milling binder layers. The lane application width of carriageway measures is 3.5m, corresponding to the actual width of a single road lane. The total measure application width is 3.5 times the number of lanes (#L) that the carriageway contains plus shoulder (+S).

3.2.3.1 APPLICATION WIDTH

In practice, the application width of M&R measures goes beyond the distinction between lane-wide and carriageway-wide designations. On the one hand, lane-wide measures have varying lane application widths that depend on the specific treatment. Moreover, for lane-wide asphalt overlays, the geometry of the road further influences the application width. The application width of carriage-way wide measures, on the other hand, is solely determined by the geometrical characteristics of the road, including the number of lanes within the carriageway and the width of the shoulder.

Lane-wide LEM rehabilitation measures can prescribe the same treatment but at different lane application widths. Even when the treatments are identical, the application widths may differ based on the specific road configuration.[9]. Figure 13 and Figure 14 schematize the lane application widths for the different road configurations.

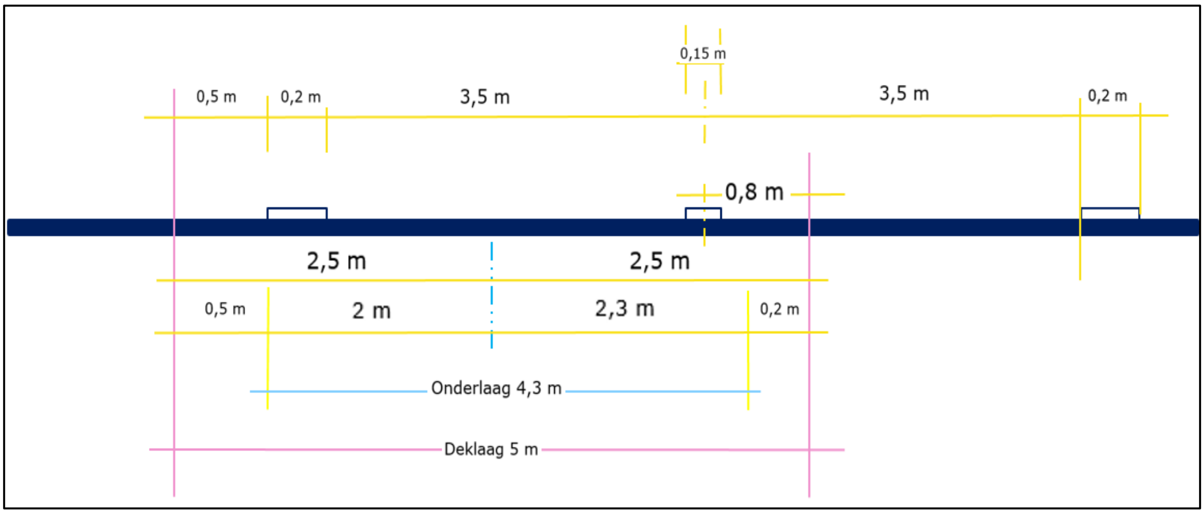

Figure 13. Lane application widths for road carriageways of two lanes + hard shoulder. Retrieved from GPO (2022).

Treatments applied to road carriageways with two lanes and a hard shoulder, representing roughly 90% of the total network roads (Hooimeijer, 2001), have a designated lane application width of 5 meters. Alternatively, the application width for treatments on roads with three or more lanes and a hard shoulder is 4 or 4.5 meters, depending on the nature of the overlay. Due to the serrations needed to mill the binder layers, a structural overlay is 4.5 meters wide, while a functional overlay is 4 meters wide. Table 7 provides a summary of the application widths of lane-wide LEM measures.

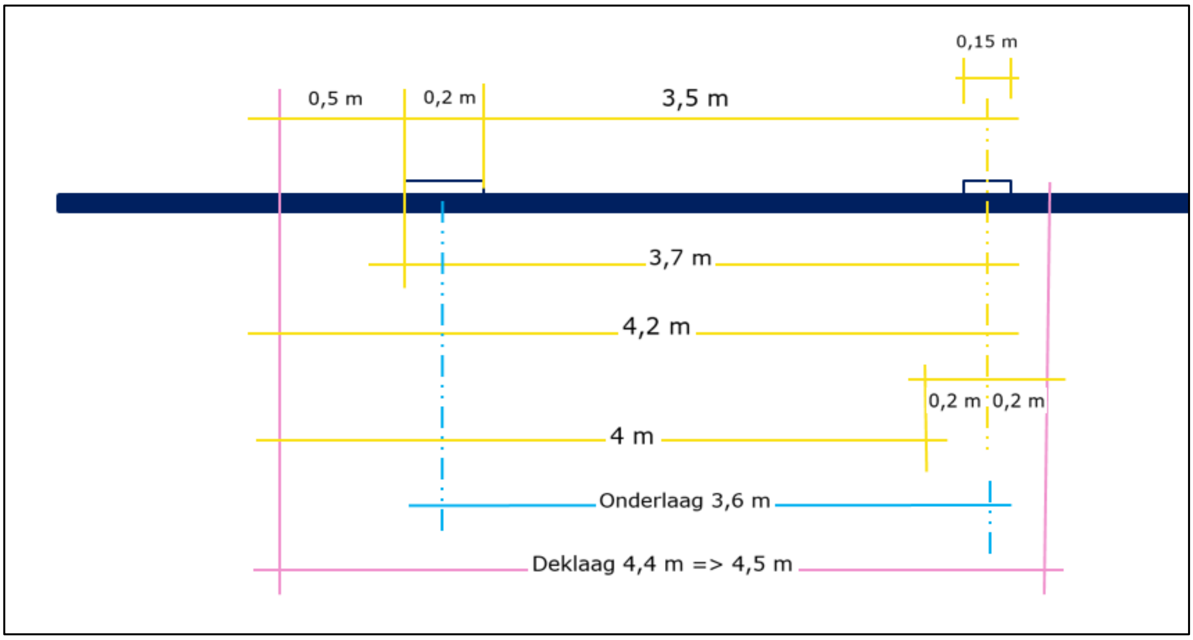

Figure 14. Lane application widths for road carriageways of three lanes or more + hard shoulder. Retrieved from GPO (2022).

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[9] Road configuration refers to the number of lanes contained in a carriageway.

Application widths for maintenance measures are marginally less than the 3.5m actual lane width. Surface roughening measures are applied to a width of 3.3 m, while BST ZOEAB treatments are applied at a width of 3.4 m. EAB is applied to longitudinal ruts, so the width of its application is twice that of the wheel paths (2x0.75m).

Table 7. Structural decomposition of lane widths for lane-wide LEM rehabilitation measures.

Road configuration	Overlay	Layer	Application width (m)
2 lanes + shoulder	Structural / functional	Surface	5
		Binder	4.3
3 or more lanes + shoulder	Functional	Surface	4
	Structural	Surface	4.5
		Binder	3.6

The application width of carriageway-wide measures considers both the number of lanes within the carriageway, standardized at 3.5 meters per lane, plus the width of the hard shoulder, which typically averages around 5 meters[10]. As a result, for carriageways with two lanes plus shoulder, an average width of 12 meters is estimated, establishing the minimum application width of carriageway-wide measures. For carriageways with additional lanes, an extra 3.5 meters is added to the total width for each additional lane.

3.3 M&R EXECUTION: WHAT IS CONSIDERED?

The M&R measures outlined in the MJPV are preliminary and thus subject to revision. The MJPV is founded on multiple assumptions, some of which pertain to the construction processes and activities associated with the measures it instructs. However, it is important to note that many of these assumptions may not align with the actual conditions and practices encountered in the actual execution of M&R works. ICO characterizes the execution of M&R measures according to the RWS asphalt standards (GPO, 2022), which serve as the basis for calculating the costs associated with M&R plans, but does not necessarily reflect the precise construction processes that occur during the execution of M&R.

This chapter describes the construction activities and assumptions that are ascribed to the different M&R measures that devise the MJPV.

3.3.1 CONSTRUCTION ACTIVITIES

For rehabilitation measures involving asphalt overlays, the main construction activities are milling and laying down asphalt, although in certain cases, laying down asphalt alone may be sufficient. Additionally, minor activities such as surface cleaning before asphalt laying and the application of road markings are considered as part of the execution of asphalt overlays. Alternatively, maintenance measures typically involve simpler processes, such as applying BSTs over the existing surface layer or using specialized machinery to roughen the surface. Appendix A breaks down the execution process of the different M&R measures into specific and successive construction activities per treatment and their characteristics.

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[10] The width of the hard shoulder can vary significantly in practice. However, for the purpose of cost calculations and measure documentation provided by the RWS (GPO, 2022), an average width of 5 meters is defined. This standardized value allows for consistent and efficient cost estimations and ensures uniformity in the application of M&R measures across different road sections.

3.3.2 CONSTRUCTION RATE ASSUMPTIONS

A crucial aspect of construction is the amount of work that can be completed per day. It is assumed that construction takes place overnight, with a 9-hour work window from 20:30 to 5:30. As required, LEM measures are applied compartmentally, whereas MM measures are applied along a continuous length.

3.3.2.1 LEM COMPARTMENTS

Compartments are sections with a defined width and length to which LEM measures are applied. Depending on the size and road configuration, a compartment can be completed in either one or two nights. The number of compartments that can be completed within the assigned time frame depends on the number of asphalt layers to be added, with lower compartment numbers corresponding to robust structural overlays and higher numbers to single-layer functional overlays and maintenance measures. Table 8 lists the different compartment specifications and characteristics.

Table 8. Compartment specifications.

Compartment specifications							
M&R type	Implementation width	Road type	Overlay type	Nights (#)	Width (m)	Width / 1 night (m)	Length (m)
LEM	Lane	2 lanes + shoulder	F, S	2	5	2.5	200
		3 lanes or more + shoulder	F	1	4	4	200
			S	1	4.5	4.5	200
	Carriageway	Starting point: 2 lanes + shoulder	F, S	2*	12	6	200
Notes: * the number of nights increases correspondingly if the road carriageway has more than 2 lanes + shoulder							

3.3.2.2 MM COVERAGE

MM measures are performed over two nights for a road configuration of carriageways of two lanes plus shoulder, covering a width of 6m per night. The maximum length that can be covered per night depends on how many asphalt layers will be applied. Functional overlays have a maximum length of 1620m and structural overlays of 720m and 420m for two and three asphalt layers, respectively. For roads with carriageways of more than two lanes plus shoulder, the number of nights to perform the M&R works increases correspondingly.

3.3.2.3 CONSTRUCTION PROCESS

To determine the coverage of compartments for LEM measures and the maximum length of MM measures, the RWS makes assumptions about the stop time required for construction equipment before the execution period ends. This stop time includes the necessary cooling down period for the asphalt, application of markings, and adjustment of traffic measures. The RWS has defined specific stop times for different types of overlays.

For functional overlays, which involve the replacement of the surface layer only, the stop time is assumed to be 1.25 hours. In the case of structural overlays with two layers, the stop time is set at 1.75 hours. For structural overlays with three layers, including the surface and two binder layers, the stop time is extended to 2.75 hours. These stop times include the cooling down period required for the asphalt.

Considering that it takes approximately 1.5-2 hours to start the asphalt application, the most favorable scenario allows for a maximum of 6.25 hours for asphalting activities in the case of functional overlays, 5.25 hours for structural overlays with two layers, and 4.25 hours for structural overlays with three layers.

The variation in the number of layers applied impacts the coverage of compartments for LEM measures and the length of MM measures. In cases where three-layer overlays are applied in one evening, LEM measures will cover fewer compartments, and MM measures will be shorter compared to other scenarios. Two lane-wide LEM measures involving ZOABTW and ZOABTF structural overlays requiring 50+50mm binder layer replacements involve four asphalt layers: QAN0103 and QAN0151. These measures are performed in one night, as they involve roads with three or more lanes plus shoulder, and cover only one compartment.

Additional assumptions considered in the definition of the measure's coverage are listed in Table 9.

Table 9. Construction assumptions for VM (GPO, 2022; Van der Pijl, 2022).

M&R activity	Theme	Description
Milling	Equipment	2 milling sets: 2 and 0.5m. If milling exceeds 800m2/hour, then an additional 2m milling machine is used.
	Availability	8 hours
	Rules	For structural overlays where several layers are removed: - Separate milling for layers with different asphalt mixtures. - The width of the layers is adjusted 20-50cm per layer to create serrations during the application of LEM lane-wide measures for carriageways with 3 or more lanes + shoulder. The adjustment of the width of the surface layers is reflected in the description of each measure in such cases (4.5m instead of 4m) so the layers below are at least lane-wide.
Surface cleaning	Equipment	Sweeper / suction vehicle for coarse material
		Road surface cleaner
	Availability	8 hours
Asphalt application	Equipment	Large asphalt set: width of 2.5 - 5m or 3 - 6m, includes 2 large and 1 small rollers
		Small asphalt set: width of 2.5m, includes 1 large and 1 small rollers
	Availability	10 hours.
	Speed	5.5m/min
	Cooling down time	For 1 layer: 0.5 hours; For 2 layers: 1 hour; For 3 layers: 2 hours.
	Rules	Relocating the asphalt machine between compartments is assumed to take 45 minutes. The deployment of the asphalt roller is decisive for the planning as it the slowest machine employed in the construction process.
Tack coat application	Quantity	0.4 kg/m2 per layer (not applicable between the top and bottom layers of full ZOABTW and ZOABTF replacements).
Marking	Equipment	1 marking set
	Availability	4 hours
	Quantity	Corresponding length of continuous and intermittent lines marked during the working nights. For LEM lane-wide, 1 continuous and 1 intermittent line. For LEM and MM carriageway wide, at least 2 continuous and 1 intermittent line (carriageways with more than 2 lanes + shoulder require more intermittent lines).

3.3.3 ASPHALT QUANTITY ASSUMPTIONS

While carrying out rehabilitation measures, more asphalt is applied and milled off in fact than is specified in theory, which is referred to as the practical and theoretical layer thicknesses. For example, the prescription of 25 mm out/in in reality can become 30mm out/in. ICO estimates the practical layer thickness for functional overlays to be 5mm greater than the theoretical layer thickness. When structural overlays are executed, the width of the surface layer is larger than the width of the binder layer due to the serrations required for construction. As the binder layers are supposed to have the same width as the surface layer, the resulting excess asphalt mixture is supposed to compensate for the extra 5 mm in layer thickness. In these instances, the practical layer thickness is equivalent to the theoretical layer thickness. The concept of theoretical layer thickness is also applicable to ZOABTW overlays as its layering requires two different asphalt mixtures.

3.3.4 TRANSPORT ASSUMPTIONS

The assumptions for the transport of new asphalt and asphalt that has been milled are based on a theoretical transport cycle plus an additional 30 minutes of waiting time for each trip. Combined transport, in which the same vehicle is used to transport both new asphalt and milled asphalt, incurs an additional 30 minutes of waiting time per trip. This results in 3.36 minutes per ton of new asphalt and 3.61 minutes per ton of milled asphalt residue for separate transport, and 2.39 minutes per ton for combined transport. LEM measures usually include separate transportation, whereas MM measures consider combined transportation.

The activities associated with maintenance measures are less complex than those associated with rehabilitation measures. For BST, transportation is treated similarly to rehabilitation measures, and the construction activities that take place are treatment application and posterior surface cleaning. A microlayer set and a cleaner and/or sweeping/suction vehicles are then required to perform such maintenance measures. In a similar fashion, the construction activities for surface roughening consider only the use of, for example, a Unimog machine and the posterior surface cleaning tasks.

3.3.5 TRAFFIC ASSUMPTIONS

It is considered that restrictions on traffic diversion measures can only be in place for a maximum of 4 kilometers on roads with two lanes plus shoulder, and for roads with three or more lanes plus shoulder, 8 kilometers.

4 LCA IN THE PM CONTEXT

As pavements generate significant environmental impacts throughout their entire life-cycle (Santero & Horvath, 2009a). LCA has become an important part of the efforts to make PM more sustainable. LCA is an approach that has been progressively embraced by transportation agencies throughout the world to account for the environmental impacts of pavements, and it has received wide acceptance from the sustainable pavement management community (Liljenström et al., 2020; Miliutenko et al., 2014; Rangelov et al., 2020; Santero et al., 2011b, 2011a; Santos et al., 2015; Van Dam et al., 2015). Numerous PM approaches integrate LCA studies into PM decision-making to facilitate a transition from conventional to more sustainable PM practices (see France-Mensah & O'Brien, 2019; Marcelino et al., 2019; Santos et al., 2015, 2017, 2018; Torres-Machí et al., 2015, 2017; Zhang et al., 2013).

This chapter provides a state of the art on LCA. It answers to the knowledge questions of:

- *What are the key aspects that needs to be considered in a pavement M&R LCA?*
- *What are the key sources of uncertainty in pavement LCA, and how do they affect decision-making in the early stages of PM?*
- *What are the most common and effective methods for quantifying and managing uncertainty in LCA?*
- *What are the limitations and challenges of using LCA and uncertainty analysis for decision-making in the early stages of PM?*

The chapter starts with defining pavement LCA and what it comprises. Second, it outlines the uncertainties in the approach and what has been proposed to address them. Following, existing pavement LCA frameworks available in the literature are investigated, as well as their function in sustainable PM. Finally, an overview of how pavement LCA is implemented in the Netherlands, as well as its current role in the Dutch PM Cycle, is provided.

4.1 INTRODUCTION TO PAVEMENT LCA

LCA is a well-established approach employed to quantify the environmental impacts associated with pavements throughout their entire life-cycle, and it has sparked a growing interest in the scientific community (Mattinzioli et al., 2021). LCA studies can be used to determine and disclose the environmental performance of a single pavement system so that the most significant impacts and opportunities for improvement can be identified, or to compare different alternatives and determine which one performs better based on their environmental impacts (Harvey et al., 2016).

LCA models all important processes and flows associated with a pavement's life cycle to represent a pavement system and determine its environmental performance. A pavement system is defined by its structure, i.e., surface, binder, and/or base layers and subgrade, and its materials, i.e., HMA, warm-mix asphalt (WMA), cold-mix asphalt (CMA), BTS, etc. The pavement life cycle usually covers production, construction, use, and EOL (Figure 15), though the specifics of each largely rely on the PM decision level hierarchy (network- or project-level) (Butt et al., 2015).

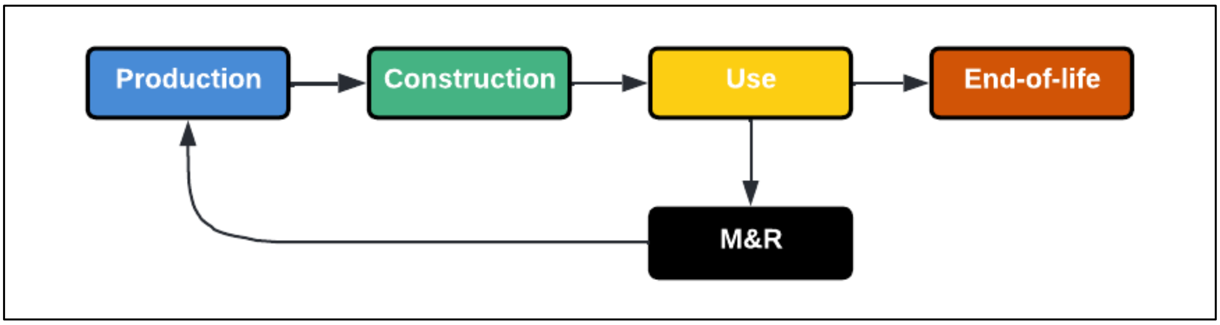

Figure 15. Life cycle of pavements.

Production encompasses the extraction and/or acquisition of raw and secondary materials, as well as their subsequent transport and transformation into asphalt materials. Construction considers processes associated with on-site pavement construction activities, including equipment use and traffic diversion measures, as well as transportation of asphalt products to the site. Use refers to the processes that occur during the service life of pavements that have an impact on the environment and are frequently tied to the characteristics of the pavements. Generally, M&R treatments are incorporated into the use phase since they are applied at successive periods throughout the entire pavements' lifespan to improve or reset their state. However, some scholars regard M&R as an independent phase (Santero & Horvath, 2009b). EOL refers to the processes related to the recycling, reuse or disposal of the pavement materials that become available at the end of pavements' service life, including transport from the construction site to the waste processing locations.

4.1.1 THE USE PHASE

The use phase is a critical component of pavement LCA studies. Among other mechanisms, it includes PVI or, in other words, the interaction between the pavement surface and the vehicles that travel on it. While the focus of LCA has been historically placed in the production, construction and EOL phases (Xu et al., 2019), the environmental impacts of the use phase may represent a large share of total life cycle impacts (Harvey et al., 2016; Santos et al., 2022). PVI is the relationship between the pavement characteristics and the vehicle fuel efficiency, determined by pavement rolling resistance (RR). As RR increases, so do the fuel consumption and the emissions generated by the vehicles moving across the road (Bryce et al., 2014; Van Dam et al., 2015). Thus, the environmental impacts of PVI are, to a great extent, determined by the pavement condition, which in turn, is greatly reliant on the adequacy of M&R (EUPAVE et al., 2016; Santero & Horvath, 2009b; Santos et al., 2018).

Many LCA studies have included PVI in their assessments due to its contribution to the environmental impacts (see Akbarian *et al.*, (2012); Gregory *et al.*, (2016); Noshadravan *et al.*, (2013); Santos *et al.*, (2022)), albeit this does not symbolizes standard practices. The actual environmental burden linked to pavements is not fairly characterized when the use phase is left outside the analysis or insufficiently represented (Santero et al., 2011c). Santos et al. (2022) showed that the environmental impacts of the use phase due to PVI are significantly greater than those related to the production and construction phases. The authors demonstrated that a pavement that is regularly rehabilitated over a 30-year analysis period, where the levels of roughness-induced RR are managed consistently, has lower environmental impacts over its entire life cycle than a pavement to which M&R measures simply not applied. This suggests the environmental benefits of controlling RR levels with M&R outweigh the environmental impacts involved in the execution of M&R, which is of special interest at network-level planning (Harvey et al., 2014; Liu et al., 2022). PVI's cumulative effects over time then have the potential to be the greatest source of environmental impacts over the course of a pavement's life.

Note that the use phase also comprise other mechanisms such as albedo (Gregory et al., 2016; Noshadravan et al., 2013; Santero et al., 2011b; Van Dam et al., 2015), concrete carbonation (exclusive for concrete pavements) (Gregory et al., 2016; Noshadravan et al., 2013; Santero et al., 2011b), lightning (Gregory et al., 2016; Noshadravan et al., 2013; Santero et al., 2011b), and leaching (Santero et al., 2011b; Van der Kruk et al., 2022). Given the preponderance of PVI in the environmental impact assessment, it stands to reason that such mechanisms might have less influence in the use-phase assessment. Nonetheless, when reliable models and data are available, their impacts should be factored into the LCA analysis.

4.1.1.1 HOW TO ACCOUNT FOR PVI?

PVI can be accounted for in LCA studies with the assistance of RR and vehicle fuel consumption models. RR models are factor relevant aspects that influence the evolution of RR over time. The most prominent attributes affecting RR are pavement roughness, macrotexture, and structural stiffness. (Bryce et al., 2014; Van Dam et al., 2015). Roughness refers to the irregularities on the pavement surface, which are typically measured in terms of the International Roughness Index (IRI) expressed in meters per kilometer. Macrotexture refers to the size of the pavement surface irregularities, which are typically measured using the Mean Profile Depth (MTD) in millimeters. Structural stiffness refers to the pavement's ability to resist deformation under load and is typically measured using the Falling Weight Deflectometer (FWD) in units of megapascals (MPa). The different RR mechanism have been addressed in the development of a number of models that attempt to predict the evolution of their values over time (see Akbarian, (2012); Akbarian et al., (2012); American Association of State Highway and Transportation Officials, (2008); Swei et al., (2018)).

Fuel consumption models that take as input RR value predictions based on its mechanisms are also available in literature. The MIRIAM model (Hammarström et al., 2012) is a Swedish model that estimates the extra fuel consumption induced by an increase of RR over time for three types of vehicles: passenger cars, heavy duty vehicles (HDV) and HDV + trailer. RR therein is measured in terms of roughness- and macrotexture. Alternatively, Zaabar & Chatti (2010) proposed a fuel consumption model based on roughness characteristics. The results that these models generate can provide the information that is required to account for PVI effects in LCA.

4.2 STRUCTURE OF AN LCA STUDY

There are four key stages of an LCA study (ISO 14044, 2006; Harvey et al., 2016): (1) goal and scope definition, (2) life-cycle inventory (LCI) analysis, (3) life-cycle impact assessment (LCIA) and (4) interpretation. Appendix B provides a breakdown of the stages of a pavement LCA study based on the reference pavement life-cycle assessment framework developed by Harvey et al. (2016).

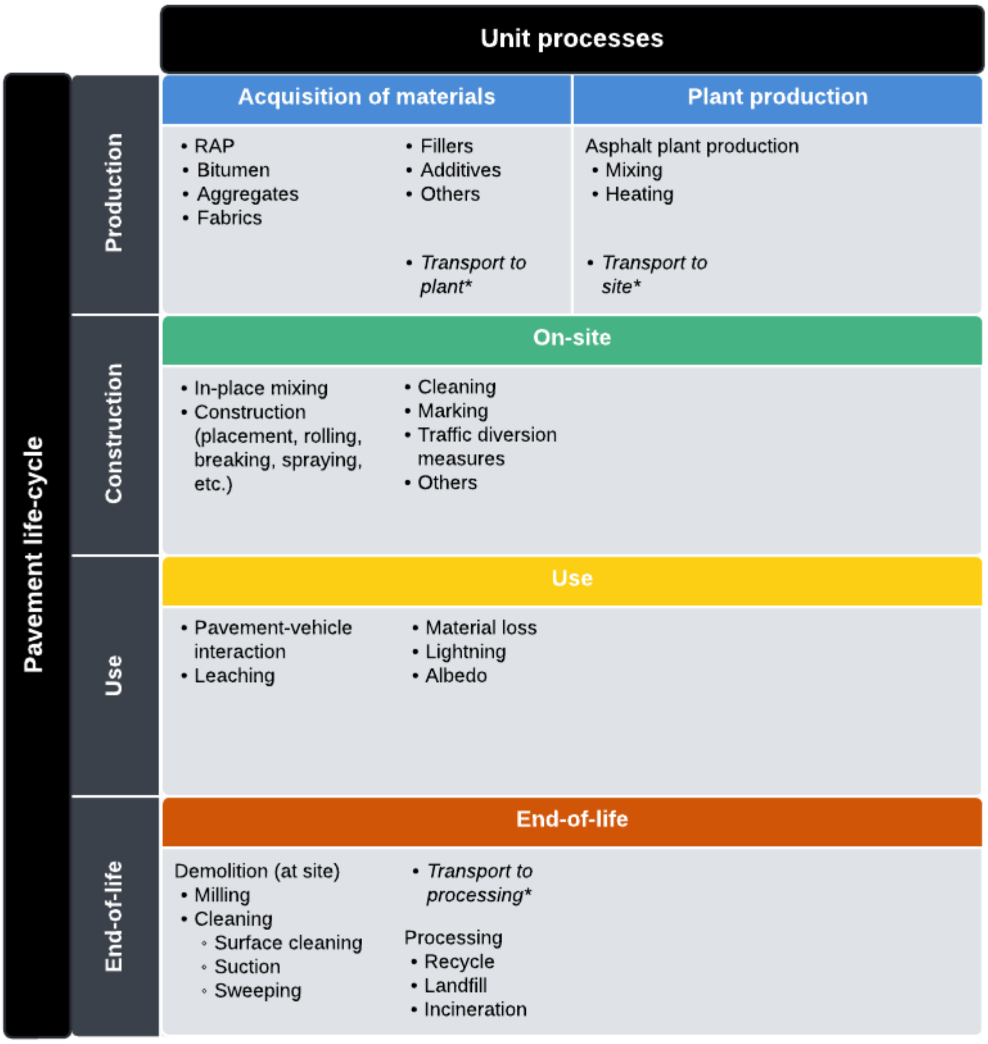

Figure 16. Compilation of unit processes included in the system boundaries of pavement systems. Based on Harvey et al. (2016).

During the goal and scope definition key features of an LCA study are outlined. Here, the functional unit (FU) and the system boundaries and life-cycle stages of the pavement system are defined. The FU is a description of the system that is studied in function of its physical dimensions and the performance standards that it must met during a defined analysis period. It is used as reference for the quantification of the inputs and outputs of the system. The system boundaries refer to the unit processes (i.e., processes that are part of the functional unit for which both input and output data are quantified) that are included and left out from the system. Cutoff criteria refer to the set of rules and procedures used to define the system boundaries of the assessment, including which processes and impacts are included or excluded based on specific criteria such as FU, geographical scope, and analysis period. Figure 16 compiles several unit processes that are generally part of asphalt pavement systems. Note that the pavement system can be partitioned into background and foreground systems. Foreground system in pavement LCA represents the direct environmental impacts associated with the system boundaries, including transport, production, construction, and EOL. The foreground system is typically modeled in detail, considering all relevant parameters, such as material quantities, transportation distances, and energy consumption during production, construction, and EOL. Conversely, the background system represents the indirect environmental impacts associated with upstream processes that provide inputs to the foreground unit processes. These upstream processes are often modeled using LCI data from external databases, such as ecoinvent or GaBi. The background system accounts for environmental impacts that occur outside the scope of the pavement LCA but are related to its foreground unit processes. In other words, the foreground system includes the direct inputs and outputs associated with the pavement's life cycle while the background system includes all the upstream processes that contribute to the foreground processes. In addition, the general strategy to be followed in the subsequent stages of the LCA research, including the documentation and justification of the choices and assumptions in the analysis, are all part of the goal and scope definition.

The LCI analysis follows the goal and scope definition. Herein, the environmental flows of the pavement system studied (i.e., inputs of material, energy and resources, and outputs of waste and pollution) are defined and quantified. To do so, a model of the process based on the FU and the system boundaries is established. The data to characterize these processes is collected from different sources (e.g., empirically or from databases such as ecoinvent), validated, aggregated, and scaled to the FU.

The LCIA follows next and involves the transformation of the environmental flows calculated from the LCI data into different environmental impacts. These are typically expressed in different impact categories associated with resource depletion, and human and natural impacts (e.g., global warming potential, water depletion, human ecotoxicity, acidification, etc.). There are numerous sets of impact categories for LCA studies called impact assessment methods (e.g., CML, TRACI, PEF, ReCiPe, etc.), and their selection is aligned with the goal and scope of the study.

Lastly, in the interpretation stage, the results of the study are presented and analyzed. The results are placed in the context of the FU and include the identification and description of the most significant environmental burdens associated with the pavement system and what they represent. Conclusions and recommendations are based on the results in relation to the goal and scope. At this stage, the limitations and uncertainties of the LCA study are discussed, as well as how they may affect the results.

An important but frequently overlooked component of LCA is the analysis of uncertainties inherent to the LCA methodology. Uncertainty analysis is recognized as an important part of the LCA studies of pavements (Harvey et al., 2016) and for other products in general (ISO 14044, 2006). However, no well-defined method or strategy for uncertainty analysis in LCA has been established. Chapter 4.3 dives into uncertainty analysis in LCA, with a clear emphasis on the pavements' context.

4.2.1 LCA TOOLS AND DATABASES

The execution of LCA studies is often assisted with specialized tools and databases. Both pavement specific and commercial LCA tools are used to evaluate the environmental performance of pavement systems. Examples of pavement-specific tools are the Athena Impact Estimator for highways, PaLATE Version 2.2, and DuboCalc. SimaPro, GaBi, Brightway2 and OpenLCA are examples of commercial tools. Some tools have their own LCI databases, but there are also a variety of independent databases that are compatible with various tools, such as the ecoinvent database and the Nationale Milieu Database (NMD). Because LCA findings vary depending on the instrument and database used, there is a growing need to develop a standardized pavement LCA framework that can be adopted by different tools, as well as to develop and routinely update verified representative LCI databases (Santos, Thyagarajan, et al., 2017).

4.3 UNCERTAINTY ANALYSIS IN PAVEMENT LCA

Uncertainty is a ubiquitous challenge in LCA, and even though it directly affects the reliability of the results, LCA studies are conventionally performed in a deterministic way, with single input and output values. The need for the consideration of uncertainties in LCA has been recognized in the past (Huijbregts, 1998; Lloyd & Ries, 2007; Santero et al., 2011a), but limited attention has been given to developing and including uncertainty analysis techniques in LCA (Bamber et al., 2020; Lo Piano & Benini, 2022), let alone in the pavement domain.

Within the pavement community, several authors have emphasized the importance of conducting uncertainty analysis in LCA to substantiate statements about the variations in environmental impacts among different pavement alternatives (Azarijafari et al., 2018; Gregory et al., 2016; Harvey et al., 2016; Liu et al., 2022; Noshadravan et al., 2013; Santero et al., 2011b). To achieve this, various approaches for addressing uncertainty in LCA studies have been proposed in the literature, providing valuable tools for obtaining more reliable estimations and comparisons of the environmental impacts of different products and services.

These methods typically look at three key uncertainty dimensions that must be adequately addressed to comprehensively understand and manage uncertainty in LCA: location, nature, and level (Walker et al., 2003). By incorporating these dimensions, researchers and practitioners can obtain a comprehensive understanding of the uncertainties associated with LCA results, enabling a more robust assessment of the environmental performance of different pavement options.

4.3.1 UNCERTAINTY DIMENSIONS

Uncertainty in LCA refers to the incomplete knowledge or predictability associated with a system, which can arise from various sources such as data inaccuracies, limitations in modeling techniques, and methodological decisions. One key dimension used to categorize uncertainty is location, which indicates the origin of uncertainties within parameters, the model itself, or the context scenario (Walker et al., 2003).

Parameter uncertainty emerges from inaccuracies in the input data used in the LCI and LCIA phases. Model uncertainty arises when there is a mismatch between the model and the real-world system it represents. Scenario uncertainty, also known as choice or context uncertainty, stems from the methodological and normative choices made during the goal and scope definition of the LCA, which can vary among practitioners and yield different effects on the results (Scrucca et al., 2020). To differentiate between the various types and sources of uncertainties addressed in their analyses, uncertainty studies often rely on the location of uncertainty (Huijbregts, 1998; Lloyd & Ries, 2007; Von Pfingsten, 2021).

The nature of uncertainty in LCA can be differentiated into two categories: epistemic uncertainty and ontic uncertainty. Epistemic uncertainty arises from a lack of information or knowledge about the system being studied and can be reduced through additional research, data collection, or improved modeling techniques. Ontic uncertainty, on the other hand, is inherent to the system itself and stems from its variability and unpredictability. It cannot be reduced but can be accounted for in the analysis (Walker et al., 2003).

The level dimension is used to measure the severity of uncertainty in LCA. It represents the degree of knowledge or ignorance about the system being studied, ranging from complete ignorance to complete knowledge (Walker et al., 2003). This dimension provides a valuable framework for qualitatively evaluating uncertainty and designing strategies to address it effectively (Igos et al., 2019; Walker et al., 2003).

Discerning between the different dimensions of uncertainty is crucial in determining the appropriate approach to address uncertainty in LCA. Location is frequently the most significant factor in the definition of the uncertainty analysis techniques employed. Researchers and practitioners may focus on addressing parameter uncertainty, scenario uncertainty, or both. The nature and level of uncertainty also influence the choice of uncertainty treatment approach. For instance, the ecoinvent method (Weidema et al., 2013) targets parameter uncertainty by qualitatively assessing data quality and estimating variability ranges. It distinguishes between input variability and data quality as examples of ontic and epistemic uncertainty, respectively.

Uncertainties in LCA can be categorized based on their position within the LCA study. The goal and scope definition stage is commonly affected by scenario uncertainties, which arise from the choices made by the LCA practitioner (Igos et al., 2019; Scrucca et al., 2020). On the other hand, parameter and model uncertainties are more likely to impact the LCI and LCIA stages (Igos et al., 2019). However, it is worth noting that many methods for dealing with parameter and model uncertainties only consider uncertainties detected in the LCI stage, neglecting those in the LCIA stage. This is an important consideration, as studies have shown that LCA practitioners often perceive uncertainties to be greater in the LCIA stage compared to the LCI stage (Qin et al., 2020).

Table 10 provides multiple examples of uncertainties in LCA based on location and nature, as well as their position within the LCA study.

Table 10. Examples of uncertainty in LCA. Based on Igos et al. (2019) and Von Pfingsten (2021).

Location	Stage position	Source	Nature
Parameter	LCI	For each foreground unit process:	
		Representativeness or data quality for each flow	Epistemic
		Variability of each flow	Ontic
	LCIA	For each LCIA indicator:	
		Representativeness of each characterization factor	Epistemic
		Variability of each characterization factor	Ontic
Model	LCI	For each foreground unit process:	
		Representativeness of flows and relationships	Epistemic
		Variability of relationships	Ontic
		Representativeness of background processes	Epistemic
	LCIA	For each LCIA indicator:	
		Representativeness of characterized substances	Epistemic
		Representativeness of modelling structure	Epistemic
		Variability of relationships	Ontic
Scenario	Goal and scope definition	Methodological choices:	
		Definition of functional unit	Epistemic
		Definition of system boundaries	Epistemic
		Definition of LCI modelling framework	Epistemic
		Definition of LCIA model	Epistemic
		Choice of LCA software	Epistemic

Gaining a comprehensive understanding of the various types and sources of uncertainty in LCA is crucial, but equally significant is the ability to effectively address and manage them. There are numerous strategies for dealing with uncertainty in LCA, including both qualitative approaches and advanced statistical techniques. The choice of an appropriate uncertainty treatment method relies on several factors, including the specific type and the severity of the uncertainties, the resources at hand, and the intended application of the study results. In the subsequent chapter, some commonly employed methods for handling uncertainty in LCA are introduced, providing insights into their respective strengths and applications.

4.3.2 HOW TO TREAT UNCERTAINTY?

The process of addressing uncertainty in LCA can be structured into five fundamental steps (Igos et al., 2019; Marsh et al., 2022). The initial step is identification, wherein the different types and sources of uncertainty within the analysis are recognized and documented. The subsequent step is characterization, involving the provision of qualitative and quantitative descriptions of these uncertainties. The third step is propagation, wherein the uncertainties are integrated into the analysis and their influence is propagated to the results. Following propagation, sensitivity analysis is performed to assess the influence of the uncertainties on the outcomes. Lastly, the fifth step is communication, which entails effectively communicating the uncertainties and their implications. Figure 17 illustrates the overarching steps involved in treating uncertainty in LCA. This chapter will offer a comprehensive exploration of each step, presenting a range of strategies to effectively address uncertainty throughout the LCA process.

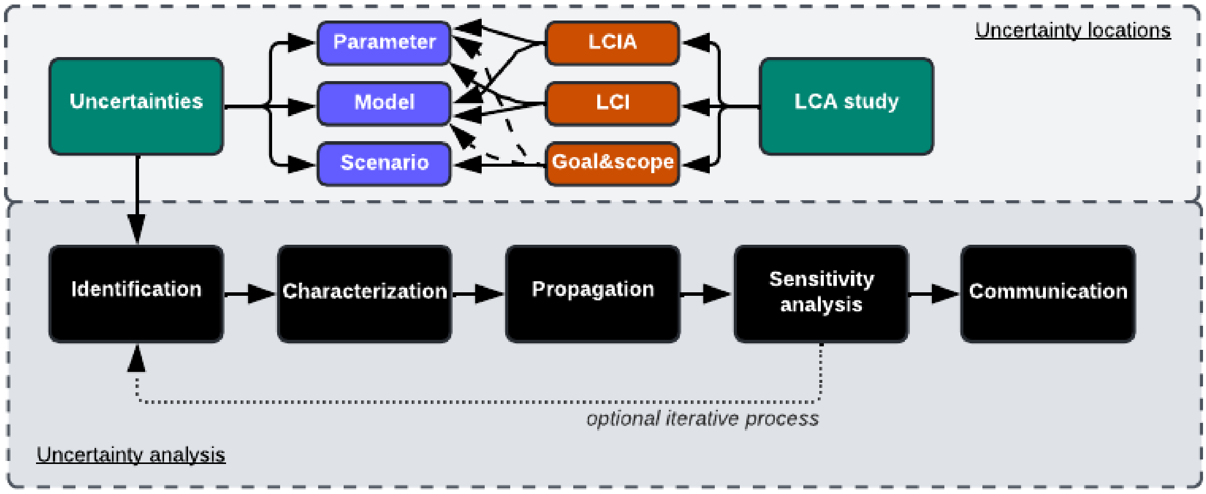

Figure 17. General uncertainty analysis strategy in LCA.

4.3.2.1 IDENTIFICATION

The first step in conducting an uncertainty analysis in LCA involves identifying the different types and sources of uncertainty present in the study. To do this, it is necessary to map out the elements with significant uncertainty within the framework (Igos et al., 2019). At this step, a decision must be made regarding which uncertainty locations will be covered by the analysis. Some methods focus on a single type of location, e.g., parameter uncertainty (Noshadravan et al., 2013), while others cover multiple locations, e.g., both parameter and scenario uncertainties (Azarijafari et al., 2018; Gregory et al., 2016).

Clear documentation of the uncertainty identification, including a list and description of the uncertainty sources and types considered in the analysis, is of utmost importance. It is important to note that uncertainties often overlap, which makes it difficult for LCA practitioners to classify them according to their dimension (Gregory et al., 2016; Walker et al., 2003). For example, some authors classify variability in certain types of input data, typically thought of as parameter uncertainty, as model uncertainty (Noshadravan et al., 2013). In other cases, methodological decisions, such as the choice of a modeling approach to describe a process flow, can be thought of as both model and scenario uncertainty (Azarijafari et al., 2018). The latter is particularly noteworthy because model and scenario uncertainty are frequently treated similarly (Igos et al., 2019). In any case, it is essential to maintain a consistent designation of uncertainties included throughout the analysis and to provide precise descriptions of them.

Parameter uncertainty in LCI arises from the different input system processes and flows included in the model. Parameter uncertainty can result from the uncertainty due to the quality of the data used to describe unit processes and flows, i.e., uncertainty resulting from the use of estimates, a lack of data verification, incomplete samples, or extrapolation from different temporal, geographical, and/or technological contexts, as well as due to its variability, i.e., measurement errors, activity-specific variations, temporal fluctuations, etc. (Weidema et al., 2013). Ideally, the estimation of parameter uncertainty should extend to all sources, both in the foreground and the background systems. In practice, however, considering the uncertainty associated with each system process and flow requires large amounts of data and resources, resulting in a very complex analysis. Consequently, the analysis may be simplified to only include a subset of processes.

An LCA executioner may always choose to focus on the background, the foreground, or both. Nevertheless, the selection of the uncertainty subset to be included in the analysis must be explicitly justified, even though some authors are frequently unclear on the approach employed to arrive at a given decision. For example, Huang et al. (2018) selected specific processes within an asphalt pavement LCA model to consider in their uncertainty analysis, but they did not explain how they arrived at their choice. If made arbitrarily, this choice could introduce scenario uncertainty due to the biases of those making it.

The decision to include and exclude certain processes in the analysis must have a sound basis to prevent further uncertainty. For example, in the pavement LCA domain, contribution-based filtering, (Cucurachi et al., 2022), a systematic prioritization strategy to select the processes the processes that contribute the most to the environmental impacts via a prior deterministic assessment, has been employed (Abed et al., 2023; Godoi Bizarro et al., 2020). The remaining processes are then treated deterministically, and only the processes that were deemed to be relevant under a well-defined set of conditions are included in the uncertainty analysis[11]. However, a more robust and generally accepted approach involves screening uncertainties through intermediate sensitivity analyses. Screening allows practitioners to identify the largest contributors to the overall uncertainty in the results, which points out to the inputs that should be included and the ones who can be dismissed, effectively reducing the number of uncertain parameters and refining the uncertainty methodology (Igos et al., 2019; Jaxa-Rozen et al., 2021b; Marsh et al., 2022) (see Section 4.3.2.4).

Pavement LCA studies usually focus on several sources of parameter uncertainty that are specific to pavements. For instance, the uncertainty associated with the effects of PVI has been the subject of numerous studies (Gregory et al., 2016; Noshadravan et al., 2013; Santos et al., 2022; Ziyadi et al., 2017; Ziyadi & Al-Qadi, 2019), particularly the uncertainty related to the models used to anticipate how the condition of pavements will change over time. The uncertainty regarding the total quantity of asphalt required per analysis period in in function of asphalt durability (Godoi Bizarro et al., 2020) has also been considered an important factor. In general, uncertainty related to the multiple processes defined in the system boundaries, e.g., on the energy consumption values for asphalt production and construction, is often categorized as parameter uncertainty. Depending on the goal and scope definition of the LCA study, it may be necessary to consider such aspects in the uncertainty analysis.

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[11] It is important to keep in mind that while this strategy provides a clear and simple method for determining which processes should be included in the analysis, it does not provide enough information to determine which of the input parameters used to describe them are more relevant for the analysis.

In pavement literature, scenario uncertainties have been categorized into two types: model and value domain (Gregory et al., 2016). Model domain uncertainties refer to the choices made by the practitioner that define the scope of the system with an appropriate value, such as the system boundaries. On the other hand, value uncertainties represent the preferences of the analyst with an appropriate value, such as the model form. In principle, these categories may overlap depending on the specifics of the analysis and the interpretations of the analyst, stressing the importance of specifying and justifying the designation of scenario uncertainty categories in the LCA study report.

Other examples of methodological choices that induce scenario uncertainty include the selection of LCA software or LCI database (Santos, Thyagarajan, et al., 2017; Scrucca et al., 2020) and the use of different allocation methods[12] (Azarijafari et al., 2018). Given the wide scenario space and ambiguous choices in LCA studies, it is recommended to always include scenario uncertainty in the analysis. To effectively map scenario uncertainties, the LCA analyst should consider the scope and goal definition and identify important decisions made for the functional unit, system boundaries, LCI and LCIA frameworks, and LCA software employed.

The most significant model uncertainties in the context of LCI are related to the representativeness of the foreground process flows, their relationships and variability, and the representativeness of the selected background processes (Igos et al., 2019). These uncertainties can arise from model simplifications, incompleteness, and/or errors (Von Pfingsten, 2021). Different methodological decisions and model parameters can induce model uncertainty, and, as such, parameter and scenario uncertainties can often capture model uncertainty. For instance, including and excluding certain system boundaries is a methodological choice made on the scope and goal definition that can result in model simplifications and incompleteness and can be traced back to scenario uncertainties (Gregory et al., 2016). Similarly, a flow associated with a specific technology can be represented with proxy data related to a similar technology, affecting not only the representativeness of the flow but also of the data used to describe it, adding both model and parameter uncertainty, which can be further captured as parameter uncertainty stemming from data quality (Weidema et al., 2013).

In the LCIA stage, the main sources of uncertainty are the representativeness and variability of the characterization and weighting factors, as well as the representativeness of the substances that are characterized, the modelling structure, and the variability of the relationships in parameter and model terms (Igos et al., 2019). Mapping uncertainty in this context involves examining the various LCIA impact categories, midpoint and endpoint indicators, weighting methods, and their components. However, LCIA uncertainties, unlike other types, have not yet been considered withing the pavement LCA domain.

4.3.2.2 CHARACTERIZATION

After identifying the sources and types of uncertainty that will be addressed in the analysis, the next step is to characterize them. Uncertainties can be characterized qualitatively and quantitatively. On the one hand, qualitative characterizations often include the evaluation of uncertainty levels against specific criteria for parameter uncertainty (Weidema et al., 2013), as well as the development of different scenarios for scenario and model uncertainty (Igos et al., 2019). Quantitative characterizations, on the other hand, are typically approached by defining minimum and maximum values and/or probability distribution functions (PDFs) to represent uncertainties (Igos et al., 2019).

Parameter uncertainty is commonly characterized adding the uncertainties of data quality and variability together (Huang et al., 2018; Weidema et al., 2013; Yu, Wang, et al., 2018). In this context,

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[12] Allocation refers to the partitioning of the input or output flows of a unit process to the product under examination in mass or economic terms.

the variability and data quality uncertainties are referred to as basic and additional uncertainty, respectively.

Basic uncertainty is usually characterized with PDFs when the sample size is large (Yu, Liu, et al., 2018), or by minimum and maximum values for smaller sample sizes (Gregory et al., 2016). When only single values are available, default uncertainty values retrieved from the ecoinvent database can be used (Azarijafari et al., 2018; Gregory et al., 2016; Noshadravan et al., 2013). Note that studies have concluded that the default uncertainty values provided by the ecoinvent method may underestimate uncertainty (Ciroth et al., 2016; Muller, Lesage, & Samson, 2016), albeit in the absence of empirical measurements, the use of ecoinvent values can serve as a starting point for assessing parameter uncertainty. Yet, as a general rule, default values should only be used when quantitative empirical measurements are lacking (Qin et al., 2020).

Additional uncertainty is evaluated using a pedigree matrix to assign a data quality index (DQI) based on various quality indicators that render its further quantitative characterization possible. The DQI is a score from 1 to 5 assigned to several data quality indicators that indicates the uncertainty level of the data used to describe a process or flow. The most notable pedigree matrix approach is the ecoinvent method (Weidema et al., 2013), which scores data quality in terms of reliability, completeness, temporal correlation, geographical correlation and technological correlation[13]. Thereafter, uncertainty values corresponding to variances are assigned to each DQI and combined with basic uncertainty to quantify the overall parameter uncertainty. The resulting PDFs usually follow a lognormal distribution. The ecoinvent method, for example, defines basic and additional uncertainties with lognormal distribution by default. However, procedures to add basic and additional uncertainties when basic uncertainty is better represented with distributions other than lognormal can be find in literature (Muller, Lesage, Ciroth, et al., 2016). Appendix C compiles fundamental stochastic knowledge required to characterize uncertainties using PDFs.

The pavement LCA community has widely employed the ecoinvent pedigree matrix to characterize additional uncertainty (Azarijafari et al., 2018; Godoi Bizarro et al., 2020; Gregory et al., 2016; Noshadravan et al., 2013; Zheng et al., 2020). This approach has also been extended to characterize the uncertainty of intermediate flows[14], assessing the data source with respect to the representation of the intermediate flow (Gregory et al., 2016). As a general rule, average data derived from specific production processes should be the first choice in characterization (NEN-EN 15804+A2, 2022; Harvey et al., 2016). In the absence of information regarding specific processes, proxy processes that are assumed to be like the one being studied may be employed. In such cases, additional uncertainty may be extended to account for this uncertainty in the same way as it does so for data quality, and further added to the basic uncertainty.

Other authors have developed similar approaches to assess data quality (Huang et al., 2018; Yu, Wang, et al., 2018), which incorporate a larger number of quality indicators into their DQI. Nevertheless, pedigree matrix approaches have been criticized for its reliance on subjective expert judgments (Qin et al., 2020). Alternative approaches to define the uncertainty factors that are used in the pedigree matrix approach empirically are found in literature (Ciroth et al., 2016), which have the potential to improve the reliability of the approach. However, their use and application hasn't been thoroughly explored yet.

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[13] The pedigree matrix approach has also found applications in LCIA. For example, Qin et al. (2020) developed a pedigree matrix for characterization factors based on the following indicators: reliability of underlying science, model completeness, temporal specification, geographical specification, and input data characteristics. However, as part of their findings, they noted that it is generally quite difficult to implement the pedigree matrix approach in LCIA.

[14] An intermediate flow refers to the inputs and outputs of processes within the life cycle of a product or service that are used to calculate the environmental impacts associated with that product or service.

To date, the conventional pedigree matrix approach is still the preferred choice to characterize additional uncertainty.

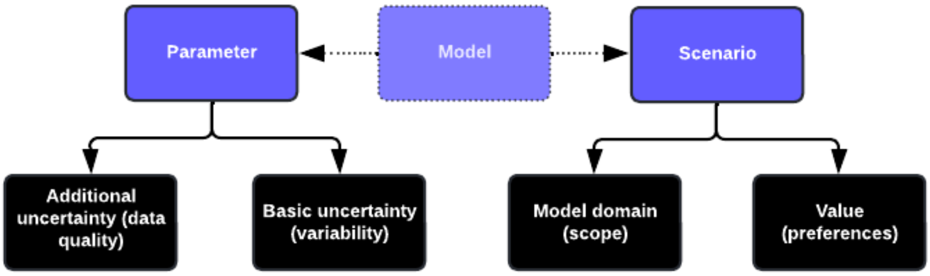

Figure 18. Uncertainty characterization. Model uncertainty is captured by parameter and scenario uncertainty.

In turn, scenario and model uncertainty are regularly characterized through the creation of alternative scenarios based on different methodological choices (Gregory et al., 2016; Igos et al., 2019; Von Pfingsten, 2021). These can be further characterized as discrete choices with equal likelihood characterized with uniform probability distributions (Azarijafari et al., 2018; Gregory et al., 2016). Expressing choices in such a way facilitates the analysis of various scenarios with different parameters and model choices combinations without specifying that one is more likely than the other (Gregory et al., 2016). Scenarios that consider the use of one allocation method over another (Azarijafari et al., 2018), the exclusion and inclusion of particular system boundaries (Gregory et al., 2016), and the definition of alternative pavement design specifications (Gregory et al., 2016; Trupia et al., 2017), are all examples of scenario uncertainties in the pavement LCA domain. Figure 18 summarizes the potential alternatives to characterize uncertainties in LCA based on their location.

In the context of pavements, several characterization methods can be used to address sources of uncertainty related to specific pavement parameters. For example, consider PVI and asphalt quantity, two important parameters in pavement design. Some researchers have employed specialized models to estimate the impacts of PVI, which incorporate probabilistic models to predict pavement condition over time. By leveraging these models, uncertainty related to PVI can be characterized as parameter uncertainty (Gregory et al., 2016; Noshadravan et al., 2013). Similarly, various techniques have been developed to quantify parameter and model uncertainty associated with prediction models (Ziyadi & Al-Qadi, 2019). For asphalt quantity, Godoi Bizarro et al. (2020) developed an equation that defines PDFs for pavement durability. This equation can be used to calculate the PDF of total asphalt quantity over a specified period, thus characterizing the uncertainty related to this parameter.

There are several LCA software tools available that offer features to help researchers characterize uncertainty (Igos et al., 2019). Some popular LCA tools such as SimaPro and GaBi provide users with a range of probability distribution options that can be used to describe uncertainty in LCI data. In addition to characterizing LCI uncertainties, other software tools like OpenLCA offer capabilities to address uncertainties at the LCIA stage. Overall, the various capabilities of LCA software to characterize uncertainty offer users a suite of options to improve the robustness of their assessments.

4.3.2.3 PROPAGATION

Once the uncertainties have been characterized, they need to be propagated to the LCA results to evaluate their impact on the outcomes. There are several methods for propagating uncertainty in LCA, including stochastic sampling, analytical approaches, and fuzzy logic (Igos et al., 2019). Some studies have compared and evaluated different uncertainty propagation techniques in LCA (Groen et al., 2014; Heijungs & Lenzen, 2014; Lloyd & Ries, 2007), and while each method has its own strengths and limitations, is apparent that researchers commonly resort to stochastic sampling, notably Monte Carlo sampling (MCS), to propagate uncertainty both in general (Bamber et al., 2020; Michiels & Geeraerd, 2020), and in the pavement domain (see Azarijafari et al., 2018; Godoi Bizarro et al., 2020; Gregory et al., 2016; Huang et al., 2018; Noshadravan et al., 2013; Santos et al., 2022; Yu, Liu, et al., 2018)[15].

MCS is a stochastic method frequently applied to propagate numerical input uncertainties characterized by PDFs to LCA results, which approximates the aggregated impacts of individual input uncertainties on the results (Heijungs, 2021; Igos et al., 2019; Lloyd & Ries, 2007). Several computational LCA tools are equipped to propagate uncertainties to the results using MCS (Igos et al., 2019). The method involves running a large number of simulations, typically around 10,000 (Heijungs & Lenzen, 2014), to estimate the probability distribution of LCA results based on the uncertainty PDFs of the inputs. In each simulation, random values are drawn from the PDFs of the inputs, and the resulting LCIA results are used to generate a PDF that characterizes the uncertainty of the LCA results, with each simulation producing a unique LCIA value. While MCS produces reliable results, it demands a significant amount of computational effort as the accuracy of the method is proportional to the sample size. Given the large computational effort that it requires, MCS is most suitable for smaller LCA models (Igos et al., 2019).

To reduce the computational time, Latin hypercube sampling (LHS), an alternative stochastic sample approach, can be used. LHS is an efficient modification of MCS that divides the input distribution into equal intervals from which a sample point is selected randomly (Groen et al., 2014; Igos et al., 2019). It guarantees that all intervals are sampled equally, and that no area is over- or under-sampled. Therefore, it is particularly useful for large LCA models or contexts where the sample size must be kept as small as possible[16].

While stochastic sampling methods are commonly used for propagating uncertainties in LCA, scenario analysis is another approach that can be useful in addressing uncertainty. Scenario analysis is a relatively easy and practical approach to analyze uncertainties in LCA. It involves the single or simultaneous variation of parameters, methodological choices and model formulations to generate a range of results based on different scenarios (Igos et al., 2019; Von Pfingsten, 2021). Scenario analysis is particularly useful for analyzing the uncertainty associated with a limited number of discrete options (Von Pfingsten, 2021).

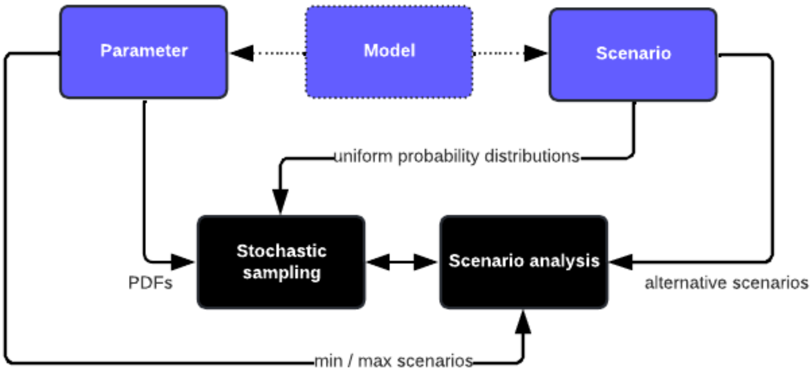

Figure 19. Uncertainty propagation. Model uncertainty is captured by parameter and scenario uncertainty. Analytical and fuzzy logic approaches are left out of the depiction.

In the context of pavement LCA, scenario analysis has been used to evaluate the effect of different methodological decisions and model formulations, such as the definition of the functional unit and the inclusion of specific system boundaries (Gregory et al., 2016), , as well as to analyze the effect of different

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[15] For an initial description of other uncertainty propagation methods used in LCA (i.e., analytical methods and fuzzy logic), refer to Igos et al. (2019) and Marsh et al., (2022).

[16] Issues with stochastic sample methods such as MCS and LHS have been highlighted in literature. For a brief introduction to the topic refer to Marsh et al., (2022) and Heijungs, (2021).

allocation methods (Azarijafari et al., 2018). For parameter uncertainty, scenario analysis can provide a range of results based on the characterization of optimistic and pessimistic parameter values (Azarijafari et al., 2018). Figure 19 illustrates the potential options for uncertainty propagation in LCA.

Both stochastic sampling and scenario analysis can be combined to better understand the uncertainties and their impacts on the LCA results. Scenario analysis facilitates the variation of different scenario formulations. Stochastic sampling, on the other hand, effectively propagates parameter uncertainties characterized by PDFs to the LCA results. By combining both methods, the effects of scenario and parameter uncertainties can be examined simultaneously. For instance, in pavement LCA studies, scenario analysis has been used to analyze the effect of different methodological decisions and model formulations, while stochastic sampling has been used to propagate parameter uncertainties to the results. In a study published by Gregory et al. (2016), seven uncertain value and model domain formulations were identified and varied across 128 scenarios. For each scenario, an MCS with 1000 runs was used to propagate parameter uncertainty of the system processes and flows (previously identified and characterized using the ecoinvent method). As a result, 128 PDFs that illustrate the uncertainty of each scenario were obtained. An important remark of this study is the conclusion that the variability of the outcomes due to scenario choices can be reduced "…through consensus development processes within the decision-making community" (p.6404), such as product category rules (introduced in Chapter 4.5).

4.3.2.4 SENSITIVITY ANALYSIS

Incorporating uncertainty analysis in LCA can range from simple qualitative assessments to comprehensive quantitative analyses that include a sensitivity analysis. A complete uncertainty analysis not only characterizes and propagates uncertainties to the results, but also includes a sensitivity analysis to investigate how changes in parameters and methodological choices affect the outcomes of the LCIA (ISO 14044, 2006; Harvey et al., 2016; Michiels & Geeraerd, 2020). Sensitivity analysis is an important step in understanding the sources of uncertainty in the model results and can determine which factors require attention to reduce overall uncertainty (Igos et al., 2019; Tecchio et al., 2019). In addition, sensitivity analysis can also be applied as an intermediate step referred to as screening. It enables the iterative refinement of the overall uncertainty analysis by removing the inputs ascertained as low uncertainty contributors from the analysis (Igos et al., 2019; Jaxa-Rozen et al., 2021b; Marsh et al., 2022; Michiels & Geeraerd, 2020; Tecchio et al., 2019).

Two types of sensitivity analysis can be distinguished: local and global. Local sensitivity analysis (LSA) focuses on the impact of small changes to parameters on the LCA results, while global sensitivity analysis (GSA) examines the impact of larger variations across the entire parameter space (Igos et al., 2019). LSA involves changing one input parameter while holding all others at their nominal values. This is a simple method that is useful for identifying inputs that have a large impact on the outputs. Alternatively, GSA evaluates the sensitivity of the outputs to changes in the entire input space. GSA can provide a more comprehensive understanding of the model's behavior than LSA by considering the interaction of multiple inputs simultaneously (Igos et al., 2019).

One-at-a-time (OAT) analysis is a LSA method commonly used in LCA to identify the impact of individual input parameters on the LCA results (Igos et al., 2019). OAT involves changing one input parameter at a time while holding all other parameters constant at their nominal values. By systematically varying each input parameter, the sensitivity of the output to that parameter can be estimated, providing insight into which inputs have the most significant impact on the model's results. However, the use of OAT as a sensitivity analysis method has been criticized because of its deficient of consideration the entire space of input variables (Saltelli et al., 2019).

A correlation analysis based on the sampled results obtained through uncertainty propagation constitutes a simple and straightforward GSA strategy (Igos et al., 2019). Spearman's rank correlation coefficient (SRCC) is a commonly used method in GSA to identify the most influential parameters and scenarios in LCA studies. It quantifies the degree of correlation between input and output variables and can provide insights into which inputs are most important for the model's results.

The Sobol method is a robust and well-established variance-based GSA technique applied to understand the relationship between the inputs and outputs of a system (Saltelli et al., 2010; Sobol, 2001). It uses variance decomposition to identify the most influential input variables on the system output by quantifying their relative contribution to the variance of the output (Igos et al., 2019; Jaxa-Rozen et al., 2021b). To do so, the variables should ideally be sampled from a quasi-random low discrepancy, such as the Sobol sequence. Sobol calculates three different sensitivity indices as its output: (1) first order Sobol indices measure the effect of a single input variable on the output, (2) second order Sobol indices measure the interaction between two input variables, and (3) total Sobol indices measure the total effect of an input variable including both its direct and indirect effects through interactions with other input variables. However, this method comes at a high computational cost; $N = n(k + 2)$ samples are required for first order indices, and $N = n(2k + 2)$ for higher order indices, with n a baseline sample size, and k the number of input parameters. Furthermore, Sobol has showed convergence issues for non-uniformly distributed parameters (Renardy et al., 2021), and may not perform well when the output distribution is highly skewed (Borgonovo, 2006), and as such, variance is not an adequate proxy of uncertainty.

Some GSA methods have been introduced as an alternative to Sobol indices, seeking to address some of the method's limitations. Two notable examples are the Extra Trees algorithm (Geurts et al., 2006), and the distribution-based PAWN method (Pianosi & Wagener, 2015, 2018). Extra Trees is a machine learning algorithm that models the relationship between input parameters and model outputs by using a set of decision trees. The algorithm can determine the significance of input variables in the output by using the Mean Decrease Impurity (MDI) metric; a variable is considered important when it is associated with a large decrease in impurity. Extra Trees is a computational efficient alternative that offers similar results to total Sobol indices. It can handle datasets with a large number of parameters and produce reliable results at smaller sample sizes (Jaxa-Rozen & Kwakkel, 2018). In the context of LCA, Extra Trees has been used as preliminary screening step to identify influential parameters that should be accounted for in the uncertainty analysis (Jaxa-Rozen et al., 2021b). If the findings of the sensitivity analysis show that some aspects are decisive, executioners may choose to go back and conduct a more refined assessment (Curran, 2013).

Distribution-based global sensitivity analysis (GSA) approaches may be more effective for non-normally distributed LCA outcomes, as they represent the influence of the inputs through output distribution changes and instead of variance alone (Cucurachi et al., 2016; Jaxa-Rozen et al., 2021b). PAWN is a moment-independent, distribution-based GSA method that evaluates the importance of inputs in the analysis by assessing changes in the output cumulative distribution calculating Kolmogorov-Smirnov statistics. PAWN is a versatile GSA method that has shown similar results to Sobol indices in the LCA context (Jaxa-Rozen et al., 2021b), is applicable regardless of the output distribution, and performs at a relatively low computational cost. Both PAWN and Extra Trees provide sound GSA methods and may be useful alternatives to Sobol indices. However, they do not offer the possibility to approximate higher Sobol indices.

The number of available pavement related pavement LCA studies in which uncertainty and sensitivity analyses is performed remains limited. There are only a few examples of publications that perform both uncertainty and sensitivity analyses available, wherein the OAT (Godoi Bizarro et al., 2020) and the SRCC (Gregory et al., 2016) techniques have been employed to evaluate the sensitivity of the results to changes in the input values. To the author's best knowledge, Sobol, Extra Trees, and PAWN, have not yet been applied to the pavement LCA domain.

4.3.2.5 COMMUNICATION

Communication of the results is the last step of the uncertainty analysis (Igos et al., 2019; Marsh et al., 2022). Communication ensues after the uncertainty and sensitivity analyses have taken place. This step requires effective communication of the LCA results, uncertainties and the various components of the uncertainty treatment (Igos et al., 2019), which is critical for ensuring transparency and credibility (Gavankar et al., 2015) while avoiding biased interpretations (Igos et al., 2019; Saxe et al., 2020). Attention has been given to tasks to improve the informative capacity of LCA by identifying and developing visualization techniques that cater to both LCA experts and non-experts, including executives and decision-makers (Laurin et al., 2016). These techniques aim to effectively communicate LCA results and bridge the understanding gap between different stakeholders, enabling informed decision-making processes. Ultimately, the decision regarding how to present them is left to the practitioners (Igos et al., 2019).

Uncertainty can be communicated in value and uncertainty terms that describe the results. Note that the use of standardized, clear and complete terms to communicate uncertainty is key for effective communication. Unfortunately, it is not always clear what the designated expected value and the uncertainty numbers represent since they can be defined in many ways (Table 11). If the equivalence of the expected value and uncertainty numbers is not clearly stated, any further interpretations of the uncertainty in the results are likely to be incorrect (Igos et al., 2019).

Table 11. Possible options for value and uncertainty numbers in LCA results. Adapted from Heijungs (2021).

Expected value	Uncertainty
Outcome of deterministic LCA	Ranges (min-max values) of the outcome series
Mean of the outcome series	Standard deviations of the outcome series
Median of the outcome series	2 or 1.96 times the standard deviations of the outcome series
Mode of the outcome series	Geometric standard deviations of the outcome series
Geometric mean of the outcome series	Squared geometric standard deviations of the outcome series
	Percentile values (e.g., $P_{2.5}$ and $P_{97.5}$) of the outcomes of the series
	Standard error of the mean of the outcomes of the outcome series
	2 or 1.96 times the standard error of the mean of the outcome series
	Coefficient of variation of the outcome series

Uncertainty can also be communicated with graphics (Heijungs, 2021; Igos et al., 2019). Box plots, histograms, and half-violin plots can communicate LCA results and their uncertainty by visually representing the distribution of the environmental impacts. A box plot displays the median, quartiles, minimum, and maximum values of a dataset. A histogram represents the distribution of the LCIA results by dividing the data into a set of intervals and counting the percentage of observations that fall into each interval. A half violin plot is a combination of a histogram and a kernel density plot, with the histogram portion representing the count or density of observations in each interval and the kernel density plot portion showing the overall shape of the distribution. Box plots, histograms, and half violin plots, all enable users to identify outliers and skewness and providing a clear summary of the spread, central tendency, and shape of the results, and can aid in identifying the ranges of inputs that are most influential on the results of the LCA. Figure 20 pictures the components of the different plots.

Sensitivity analysis results should be presented in a clear and concise manner, highlighting the most influential factors and their impact on the LCA results. Their results can be communicated with a table of coefficients (Igos et al., 2019), or with graphs that compare the relative importance of the inputs (Jaxa-Rozen et al., 2021b).

In comparative LCA studies, discernibility analysis, the evaluation of the ratios between impacts, is used to make statements regarding the environmental performance of one alternative over another. (Heijungs, 2021; Igos et al., 2019; Mendoza Beltran et al., 2018). It is commonly employed in comparative LCA pavement studies that consider the impact of uncertainty on the outcomes (Azarijafari et al., 2018; Gregory et al., 2016; Huang et al., 2018; Noshadravan et al., 2013; Santos et al., 2022).

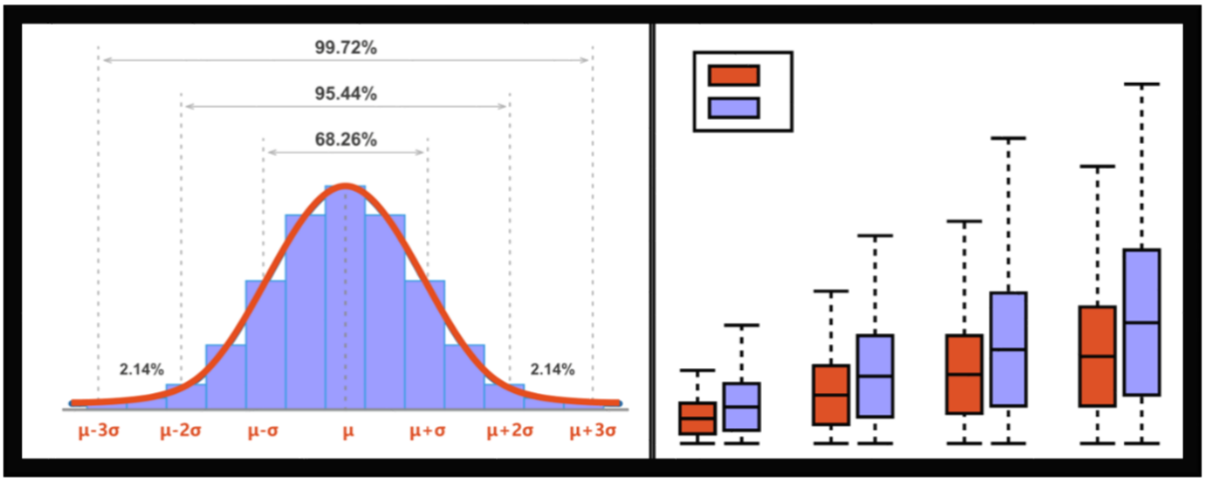

Figure 20. Graphical representation of uncertainty. To the left, histogram (in purple) and kernel density plot (in red): μ = mean (value), σ = standard deviation (uncertainty). To the right, box plot: The box represents the middle 50% of the data, the line inside the box represents the median, the whiskers represent the spread of the data, and the outliers (not shown in the figure) are data points that fall beyond the whiskers.

While there is no harmonized way of communicating uncertainty in LCA, it is essential to be transparent about the various sources of uncertainty throughout the analysis and their impact on the results (Igos et al., 2019). Providing clear and concise information on the uncertainties, whether for a single product or a comparison of them, can improve the reliability and credibility of the LCA results and enable better-informed decision-making.

4.3.3 BARRIERS TO INCORPORATION

Despite the growing recognition of the importance of uncertainty analysis in LCA, there are several barriers that hinder the widespread adoption of such. These barriers include the absence of a standardized uncertainty analysis methodology (Igos et al., 2019; Marsh et al., 2022), limited access to uncertainty information (e.g., basic uncertainty data) (Marsh et al., 2022; Suh & Qin, 2017; Weidema et al., 2013), restricted availability of uncertainty analysis methods in LCA software (Igos et al., 2019; Marsh et al., 2022), inconsistencies in scope of the analysis and lack of transparency in reporting (Marsh et al., 2022; Saxe et al., 2020), deficient communication of uncertainty assumptions, methodology and results (Heijungs, 2021; Marsh et al., 2022), the significant time and resources required for uncertainty assessments (Heijungs, 2020; Igos et al., 2019; Jaxa-Rozen et al., 2021b; Marsh et al., 2022), the lack of practical guidance (Marsh et al., 2022), and the complexity of the methods themselves (Igos et al., 2019; Marsh et al., 2022; Saltelli et al., 2019). Addressing these barriers will be crucial to promoting a more comprehensive and reliable assessment of environmental impacts in LCA.

4.4 LCA IN THE EARLY STAGES OF PM

As the early stages of PM are plagued by uncertainty, one of the top priorities for the application of LCA in this context is the development of reliable LCA approaches that account for the uncertainties in the analysis (Liu et al., 2022). Moreover, the use of LCA in the early planning stages of PM requires (1) default data that is nation specific and approved by the transportation agency, (2) flexibility to replace default data by project-specific data, (3) reliable results that complement other decision-making tools (Liljenström et al., 2020; Liu et al., 2022), and (4) system boundaries that are adequate to the decision level hierarchy (Butt et al., 2015). First, default data enables the calculation of environmental impacts in the absence of project-specific information. The data must be representative of its context and legitimately accepted. Second, the LCA model should provide flexibility to shift default data to project-specific data as new information becomes available as the PM process progresses. This will provide a platform for seamless updating of the model and its results. Third, the LCA results must be able to be evaluated alongside other important criteria considered in the decision making of PM. M&R is a complex and multi-faceted problem in which the interplay between multiple factors and variables often requires a holistic approach. Lastly, it is important to recognize that certain system boundary attributes hold varying degrees of importance at different stages of PM. Specifically, the consideration of PVI as a mechanism may not provide significant decision support in the later stages of PM, but it can still be decisive when addressing the early PM planning stages (Harvey et al., 2014; Liu et al., 2022)

There are several multi-dimensional frameworks and models that quantify and integrate the environmental impacts associated with choices made in the context of PM (Chen et al., 2022; Choi, 2019; France-Mensah & O'Brien, 2019; Marcelino et al., 2019; Santos et al., 2015, 2018; Santos, Flintsch, et al., 2017; Torres-Machí et al., 2015, 2017; Zhang et al., 2013). Notable features of these models are that they usually are customizable and complementary. In other words, they adapt to their context, are flexible to changes and new information, and supplement traditional cost-technical assessments with environmental information for more informed decision making. In addition, these models and frameworks deliver potential LCI data sources and help decide which factors are most essential to include in a pavement LCA (Liljenström et al., 2020). However, they don't usually address the particular challenges of conducting LCA studies in the early stages of PM (Liljenström et al., 2020; Miliutenko et al., 2014), when practitioners are concerned about the availability of input data and the usefulness of the LCA results for decision making (Liljenström et al., 2020). Moreover, most of these frameworks are standalone tools that are not integrated with PMS and are not designed for large-scale network-level PM (Chen et al., 2022).

PMS are decision-support systems (DSS) that assist the PM process and can be employed at both the network- and project-level stages. Traditionally, PMS perform three key functions: (1) regular collection of pavement condition data, (2) organization and storage of collected data in a computer database, and (3) analysis of the data to determine and allocate cost-effective M&R measures as needed (FHWA, 2013). LCA can directly inform decision-making within the PMS or be conducted externally and incorporated as standards. Decision examples include selecting M&R design lives, treatments, and trigger levels for (a) inclusion in PMS decision trees or (b) comparison within the PMS for alternative design lives per segment. Environmental impacts must be considered therein, taking into account network-specific factors such as pavement type, condition, traffic levels, climate, materials, and contractor capabilities, which can vary between and within networks (Harvey et al., 2014).

4.5 LCA IN THE DUTCH PAVEMENT SECTOR

In the Netherlands, the use of LCA has become normative to assess the environmental performance of asphalt pavement products, services, and projects. The development of Environmental Product Declarations (EPDs) for asphalt products (i.e., a standardized document that states the life-cycle environmental impacts of asphalt products) is regulated by an official set of specific rules, requirements, and guidelines known as asphalt *product category rules (NL-PCR)* (Van der Kruk et al., 2022). As such, the NL-PCR provides a platform to evaluate the environmental impacts of public and private asphalt related projects in the Netherlands.

The NL-PCR covers the assessment of a variety of asphalt mixtures and products that are key to pavements systems, in addition to the generic calculation rules to draw up EPDs for construction products prescribed by the *Determination Method* (*Bepalingsmethode)* (Nationale Milieudatabase, 2020) and its European parent norm *EN 15804* (NEN-EN 15804+A2, 2022). Performing official asphalt pavement LCA studies in the Netherlands commands the use of the documents thereof.

In the NL-PCR, the system boundaries for a new asphalt layer are divided into the fundamental pavement life-cycle phases, thereby referred to as modules, and displayed in Figure 21. *Production (A1-A3)* covers the materials and processes required to produce the asphalt mixture of a new asphalt layer. Construction *(A4-A5)* considers the activities and equipment needed to execute the laying of the asphalt mixture/product. *Use (B1-B3)* comprises the processes of leaching and material loss, and the maintenance activities that take place during the service life of the new asphalt layer that exert an influence on the environment. *End-of-life (C1-C3)* includes the activities related to asphalt removal at the end of its service life, from milling to recycling. The *considerations outside the system boundaries(D)* refer to the benefits and burdens of associated with the use of secondary materials outside the defined system boundaries of the new asphalt layer.

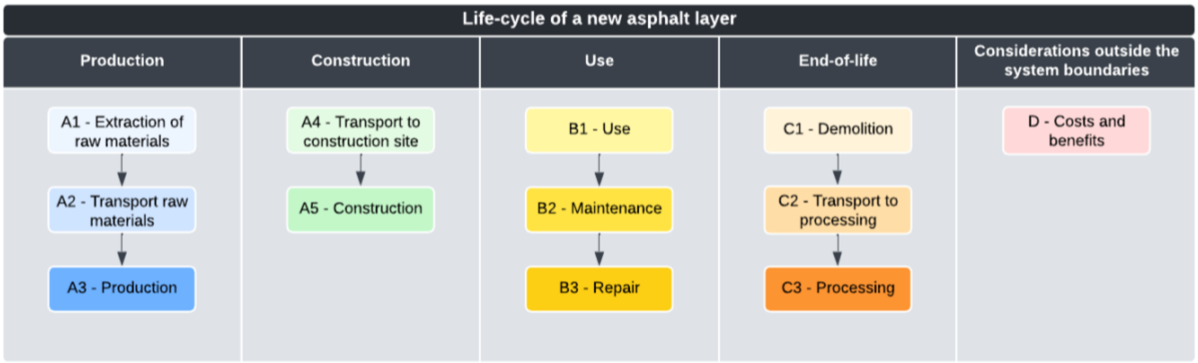

Figure 21. System boundaries of a new asphalt layer in the NL-PCR (Van der Kruk et al., 2022).

Construction (*A5*) and demolition (*C1*) are often carried out together in one project. In practice, the removal activities pertinent to the life cycle, and by extension the waste transport and processing activities in modules *C2* and *C3*, would apply to the asphalt layers that have to be removed so a new asphalt layer can be laid down (Vos-Effting et al., 2018). However, the PCR is not clear on whether modules *C1-C3* should indeed be understand in such a way, or if they should instead involve the future removal of the new asphalt layer laid down in *A5*. This emphasizes the need for clear and transparent goal and scope definition reporting.

The NL-PCR delivers a comprehensive framework for evaluating the asphalt mixtures/products used in Dutch pavements and the EPDs associated with them. However, it is important to mention that the use of the NL-PCR for the evaluation of M&R is not as straight forward as it is for new asphalt pavement projects. M&R therein is treated as a phase of the entire life cycle of pavements that is exclusively limited to maintenance measures that are addressed as project specific. Rehabilitation measures, namely asphalt overlays, are considered a new asphalt layering, and reasonably treated as such. Although this LCA treatment is not per se incorrect, the nuances between a new pavement project and a M&R project are likely to be overlooked when M&R is approached in such a way. Notwithstanding this apparent limitation, Dutch agencies and the industry alike adhere and accommodate to the NL-PCR to assess the environmental performance of M&R plans and projects as it provides a fixed and common ground to perform LCA studies among different actors. In addition, the NL-PCR provides useful pavement reference data that is specific to the Dutch context and can be used to conduct LCAs in the absence of project information.

In addition to the NL-PCR, the NMD, a Dutch-specific LCI database for construction projects, contains environmental data on construction products supplied by the industry and can be used to calculate the environmental impacts of construction projects. The NMD has a process database that includes a broad range of processes used to model environmental flows and is predominantly based on the ecoinvent3.6 database. The NL-PCR largely instructs the use of the NMD to certify that the data employed in asphalt LCA studies is representative of the Dutch context[17]. The use of the NMD process database, however, is restricted to the LCA licensed software SimaPro and DuboCalc, which limits its applicability and use

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[17] The NL-PCR occasionally recommends using ecoinvent processes as an alternative to NMD processes.

across different practitioners. Furthermore, access to the database requires a costly yearly investment, which presents a barrier to its widespread use in the Dutch context.

4.5.1 ENVIRONMENTAL COST INDICATOR OVERVIEW

The environmental cost indicator (MKI) is a single score weighting indicator designed to consolidate and standardize the monetary value of various environmental impacts. In the Dutch context, MKI is employed to communicate the LCIA results of construction works. The MKI values are based on shadow pricing[18], an environmental valuation method used to estimate the monetary value of environmental impacts that are not reflected in market prices. The current MKI values per environmental impact category, as conceptualized by the CML-NMD LCIA method, are displayed in Table 12.

Table 12. MKI values for CML impact categories. Retrieved from Hillege (2020).

Impact category	MKI value (€/unit)
Abiotic depletion (kg Sb eq)	0.16
Abiotic depletion of fossil fuels (MJ)	0,00077
Global warming 100a (kg CO2 eq)	0.05
Ozone layer depletion (kg CFC-11 eq)	30.0
Human toxicity (kg 1,4-DB eq)	0.09
Freshwater aquatic ecotoxicity (kg 1,4-DB eq)	0.03
Marine aquatic ecotoxicity (kg 1,4-DB eq)	0.0001
Terrestrial ecotoxicity (kg 1,4-DB eq)	0.06
Photochemical oxidation (kg C2H4 eq)	2.0
Acidification (kg SO2 eq)	4.0
Eutrophication (kg PO4--- eq)	9.0

The validity of MKI, and monetization techniques alike, is often put into question due to the complex economic methods for sustainability assessment employed to valuate pollution damages and their uncertainties (Liu et al., 2022). Additionally, the MKI values that are currently employed in the construction sector were calculated using shadow prices from the year 2000 (De Bruyn et al., 2023), which have not been revised since then and are likely obsolete. The MKI methodology is also limited by the impact method, as there are no MKI values applicable to environmental impacts other than those employed by CML. As the Netherlands, is currently transition to the impact categories indicated by the Product Environmental Footprint (PEF) methodology, (Section 5.2.1.7), the future of the MKI values is undetermined. Currently, it is uncertain whether new MKI values for the PEF impact categories will be developed or whether a new weighting system will be implemented.

4.5.2 LCA IN DUTCH PM

LCA is routinely employed in the procurement stage of both new pavements and M&R projects as part the green public procurement strategy followed by the RWS (European Commission, 2013; Van Geldermalsen, 2020). Once awarded based solely on lowest bid, public contracts now frequently involve a compromise between cost and quality. This allows public authorities to select contractors based on criteria that go beyond cost and bids that offers the best value for money. Consideration is frequently given to quality features like design, risk management, and sustainability. This particular type of procurement method is known as Most Economically Advantageous Tender (MEAT) (European Commission, 2013; Van Geldermalsen, 2020).

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[18] For more information regarding the calculation of the MKI weighting values, refer to De Bruyn et al. (2023).

Tenders are internally assisted by the DuboCalc tool, an LCA software developed in house that calculates the environmental impacts of infrastructure projects. DuboCalc is a simple LCA tool with restricted functionalities; it only permits the modelling of foreground processes, and its output is exclusively deterministic. DuboCalc is directly linked to data from the NMD and is harmonized with the Determination Method (Nationale Milieudatabase, 2020). It is mainly employed to estimate the environmental impacts of infrastructure projects in the tender process.

During the tender process, contractors are required to quantify the environmental impacts associated with their M&R project proposals, which are characterized with MKI values. The RWS provides bidders with a range of estimated MKI values for a given project. The closer that the bidders are to the lower MKI bound, the larger the benefits that are awarded to their proposals. In other words, M&R bids with lower MKI values are granted larger discounts to their total bid cost, albeit this does not necessarily guarantee the best environmental performance. The most economical strategy does not denote the most sustainable strategy (Faghih-Imani & Amador-Jimenez, 2013). For more information about the use of LCA and MKI during procurement, refer to Chapter 6.2.

Although the possibilities of using DuboCalc and MKI values in other stages of the Dutch pavement management cycle have been explored (Mentink, 2021; Mentink et al., 2020), the use of LCA beyond the procurement stage has not been methodically implemented yet.

5 DESIGN

This chapter outlines the final design requirements that guide the design tasks and presents the main design product of this EngD project: the EPMF. It embodies the answer to the knowledge question of *what are the key components and functionalities of an LCA-based EPMF that can effectively address the stakeholder goals and requirements and incorporate uncertainty?*

The EPMF is composed by two main components: the LCA (section 5.2) and the uncertainty frameworks (section 5.3), previously introduced in the EPMF's design architecture (Chapter 2.5). This chapter presents, explains, and justifies the designs of both, as well as their interactions.

The preceding chapters, which investigate the problem both practically and theoretically, serve as a guide for the design tasks. The background information and literature review provided in these chapters form the basis for the design and its requirements. Additionally, the validation tasks conducted during the project's development provide valuable insights that are considered during the design process. Although only the final design iteration is presented in this document, the design considerations obtained from the validation phase are integrated into the design requirements and are elaborated further in Chapter 6.

As stated in the design scope and boundaries, the EPMF's design is based on the early PM stages, specifically in the context of ICO, and thus relies on what is applicable to its context. The EPMF is a structured approach used to direct and incorporate the evaluation of environmental performance during the early stages of PM. Even though it is designed specifically for the context of ICO, the EPMF is intended to be interpreted as a set of standards and guidelines, and as such can be replicated and adapted to other contexts. The potential for generalization to other contexts is discussed in Chapter 7, which comments on the final EPMF design.

Some of the design features of the LCA and uncertainty frameworks, including strong points of their design, caveats, and improvement recommendations, are discussed within this section. The main discussion points are further discussed in Chapter 7.

Digital applications of the design that embody its different elements, namely excel spreadsheets, Python scripts and LCA models, are provided as supplementary material and further discussed in Chapter 7. These tools serve as a proof of concept and showcase one of the potential approaches to render the EPMF instrumental and support its application and future implementation.

5.1 DESIGN REQUIREMENTS

This section presents the final design requirements for the EPMF, which have been identified based on stakeholder goals and requirements outlined in Chapter 2.1, as well as the results of the literature review and validation tasks. It answers to the knowledge questions *of how can the LCA-based EPMF be designed to facilitate usability and integration into ICO's existing operations and decision-making processes*? The requirements are presented at two levels: the EPMF level and the subcomponent level. The EPMF design requirements are focused on ensuring scientific soundness, transparency, flexibility, and compatibility with existing tools and frameworks. The LCA framework requirements aim to cover all relevant environmental impact categories, use up-to-date and representative data sources, and incorporate scientific soundness in the methodology. The uncertainty framework requirements aim to provide a comprehensive and transparent method for assessing and communicating uncertainties associated with LCA results, using scientifically sound methods, and incorporating expert knowledge where appropriate. Overall, the EPMF design requirements aim to develop an approach that complements ICO's current decision-making process, without changing it, and offers additional criteria for assessing the suitability of M&R plans.

The design requirements and their relation to the stakeholder goals are as follows:

LCA FRAMEWORK:

1. The LCA framework should be capable of accommodating all relevant types of pavements and M&R measures used in the MJPV. *Related to applicability.*
2. The LCA framework should cover all relevant environmental impact categories and consider the full life cycle and appropriate system boundaries of M&R measures. *Related to completeness and relevance.*
3. The LCA framework should be based on scientific and practical accepted LCA methodologies and use relevant literature to ensure the accuracy and validity of its results. *Related to scientific soundness.*
4. The LCA framework should use up-to-date, reliable LCI data sources that are representative of the context in which ICO operates. *Related to representativeness.*
5. The LCA methodology should be transparent and clearly communicated to stakeholders, including assumptions and limitations. *Related to clarity/transparency.*
6. The LCA framework should be flexible enough to allow for the incorporation of new data and methods as they become available. *Related to flexibility.*
7. The LCA framework should be compatible with IVON2, and its output should serve as input for the M&R plans. *Related to compatibility.*

UNCERTAINTY FRAMEWORK:

1. The uncertainty framework should be able to capture the uncertainties associated with a wide range of M&R measures for different types of pavements. *Related to applicability.*
2. The uncertainty framework should consider all sources of uncertainty relevant to M&R measures in the context of ICO and the early stages of PM, to provide a comprehensive and complete assessment of the overall uncertainty associated with LCA results. *Related to completeness and relevance.*
3. The uncertainty framework should characterize uncertainties with data that is representative of the context.
4. The uncertainty framework should provide a comprehensive and transparent method for assessing and communicating the uncertainty associated with LCA results. *Related to reliability and clarity/transparency.*
5. The uncertainty framework should be based on scientifically sound methods and incorporate expert knowledge where appropriate. *Related to scientific soundness.*
6. The uncertainty framework should be flexible enough to allow for the incorporation of new data and methods as they become available. *Related to flexibility.*
7. The uncertainty framework should be compatible with IVON2 and the LCA framework, and its output should be integrated into the EPMF results. *Related to compatibility.*

OVERALL EPMF:

1. The EPMF should be user-friendly and clearly communicate its methodology, results, and uncertainties to stakeholders. *Related to clarity/transparency.*
2. The EPMF should deliver a reliable platform to evaluate the life cycle environmental impacts of different M&R measures in the context of ICO. *Related to reliability.*
3. The EPMF should complement ICO's current decision-making process without changing it and offer additional criteria for assessing the suitability of M&R plans. *Related to complementarity.*
4. The EPMF should be flexible enough to allow for the incorporation of new data and methods as they become available. *Related to flexibility.*
5. The EPMF should be scientifically sound and based on the literature on LCA and sustainable pavement management, and further contribute to it. *Related to scientific soundness.*
6. The EPMF should integrate the knowledge and tools already used by RWS provided their suitability for the EPMF, such as DuboCalc. *Related to integration and compatibility.*

5.2 LCA FRAMEWORK

The LCA framework sets the standards to assess the life cycle environmental performance of the M&R plans generated by ICO. It provides a solution to the question of *how can the LCA methodology be tailored to assess pavement M&R in the early stages of PM?*

The LCA framework places the attention on M&R measures applied to asphalt pavements located on the main road network of the Netherlands. The specific collection of M&R measures factored into the design of the framework are those that ICO prescribes in the MJPV (found in Table 5 and Table 6). However, the framework has the potential to be generalized to other measures (see Chapter 7.3).

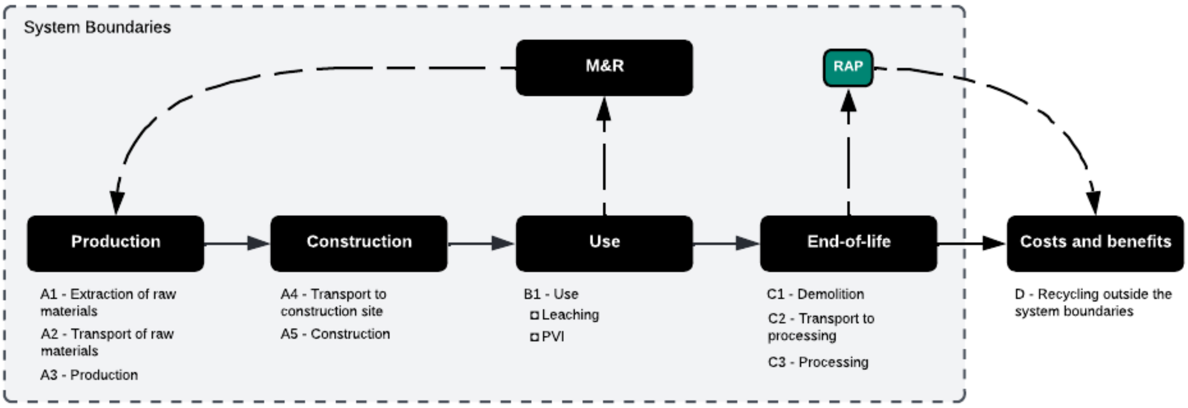

Figure 22. Pavement M&R life cycle.

The LCA framework treats M&R measures as independent asphalt products with their own life cycle (Figure 22), separate from that of a new asphalt layer. Incorporating M&R as a life-cycle phase of pavements is important when pavements are evaluated over extended time periods during which multiple M&R cycles occur. When this is not the case, pavement managers need reliable information regarding the M&R decisions that they take over the span of one M&R cycle, from the moment in which a M&R measure is applied to the moment right before a new one is needed. To do this, the framework unambiguously captures fundamental characteristics of M&R measures in their context, such as its classification as either MM or LEM, what they specifically involve, and the pavement materials and structure that they cover. The recognition of measures in their entirety provides a platform for a clearer and more direct assessment of M&R.

This framework draws upon the LCA framework developed by Harvey et al. (2016), alongside the Determination Method (Nationale Milieudatabase, 2020) and the asphalt NL-PCR (Van der Kruk et al., 2022). Literature on LCA and sustainable pavement management, particularly that compiled in Chapter 4, was also employed in its development. As a result, this framework provides a more suitable LCA framework for early PM and contributes to the ongoing efforts to standardize LCA practices across the asphalt sector. Its widespread use can then foster more sustainable PM practices among road agencies, clients, contractors, and LCA practitioners.

The following sections explain how the different stages of a pavement LCA are addressed in the LCA framework. An application of this framework is provided in Chapter 6.1.

5.2.1 GOAL AND SCOPE DEFINITION

5.2.1.1 GOAL

The goal of the LCA framework is to calculate the environmental impacts of the M&R treatments prescribed in the network-level plans. It particularly aims to inform ICO about the environmental impacts of their plans during the preparation of the MJPV.

The LCA framework's intended audience are pavement managers (i.e., ICO) who make decisions about which network-level M&R strategy to follow.

5.2.1.2 PRODUCT DEFINITION

The focus of analysis in this study is the pavement system involved in the M&R measure under examination. The pavement system is described in terms of its structure and materials, where the asphalt layers that are intervened, added, and removed are considered as the structure (i.e., surface [top and bottom layers, applicable to ZOABTW and ZOABTF] and binder layers) and the associated asphalt mixtures or products are referred to as the materials.

Table 13 Product definition information template.

Rehabilitation measure information						
RWS code						
Type (LEM or MM)						
Width (lane- or carriageway-wide)						
Road configuration						
Carriageway width with shoulder (m)						
Carriageway width without shoulder (m)						
Overlay type						
Asphalt layers	Surface (top)		Surface (bottom)		Binder	
Layer in/out	In	Out	In	Out	In	Out
Mixture						
Thickness (mm)						
Lane application width						
Total measure width						
Right lane average lifespan (years)						
Other lanes average lifespan (years)						
Carriageway average lifespan (years)						
Density (kg/m3)						
Area (for 1km of measure) (m2)						
Volume (for 1km of measure) (m3)						
Weight (for 1km of measure) (ton)						
Tack coat layers (for 1km of measure) (#)						
Tack coat total quantity (0.4 kg/m2) (ton)						
Analysis period						
Maintenance measure information						
RWS code						
Type						
Treatment						
Surface layer type						
Surface layer age (years)						
Lane application width						
Area (for 1km of measure)						
Weight (for 1km of measure) (ton)						
Life extension (years)						

In addition to the pavement system, a comprehensive breakdown of the measure and the treatment it prescribes must be included in the product definition. Table 13 provides a template with information of the M&R measure that should be provided as part of the product definition, most of which can be retrieved (or calculated) directly from the MJPV. For an example on how the template is filled, refer to Chapter 6.1. The application width of M&R measures is not explicitly recorded in the MJPV. Instead, the total surface area in square meters of the M&R measure indicated is delivered, which, when combined with the length of the road segment, allows for the derivation of the application width for lane-wide measures. In other words, the application width can be inferred from the total surface area and road segment length. For carriageway-wide measures, the total surface area recorded in the MJPV also includes the shoulder's surface (whose width is considered equal to 5m).

The suggested approach for this early PM stage, given the limited project information available, is to use the Dutch branch reference asphalt mixtures as described in the NL-PCR (Van der Kruk et al., 2022) and in publicly available LCA studies on the subject (Bak et al., 2022; Schwarz et al., 2020; Vos-Effting et al., 2018) (see section 5.2.1.8 for a detailed explanation on data requirements) for the characterization of pavement materials. At this stage, the exact version and composition of the asphalt mixtures that will be implemented in M&R is unknown, so ICO must rely on standard asphalt mixtures data. Table 14 lists the different branch reference mixtures that can be used to characterize the materials of the pavement system in the context of rehabilitation measures, typically featuring various versions of baseline mixtures with different RAP contents or bitumen. The choice on the specific version of the branch reference mixture to designate to a measure is left to the practitioner and is further addressed on Section 5.3.1.2. The branch reference mixtures are only applicable to rehabilitation measures.

Table 14. Branch reference mixtures (Van der Kruk et al., 2022).

Pavement material	ID	Branch reference mixtures
AC Surf	1	AC Surf
	2	AC Surf, 30%RAP
	3	AC Surf, modified bitumen
	4	AC Surf, modified bitumen, 30%RAP
AC Bind	5	AC Bind, 50%PR*
	6	AC Bind, modified bitumen, 50%RAP
ZOAB	7	ZOAB
DZOAB	8	DZOAB
	9	DZOAB, 30%RAP
ZOABTW and ZOABTF	10	ZOABTW and ZOABTF, top layer, modified bitumen
	11	ZOABTW and ZOABTF, bottom layer
	12	ZOABTW and ZOABTF, bottom layer, 30%RAP
SMA	13	SMA 8-11
	14	SMA 8-11, modified bitumen
DGD	15	Noise reducing SMA surface layer

The product definition of maintenance measures is handled slightly differently. BST treatments, specifically ZOEAB and EAB, should also be defined in terms of the structure and materials of the pavement system. The structure refers to the pavement layer to be intervened, which in this case is always the surface layer, and the materials refer to the ZOEAB and EAB mixtures. Surface roughening, which does not require the use of asphalt mixtures or BST, may simply require the use of specialized equipment to improve the surface condition. In such instances, the pavement structure suffices to define the pavement system (i.e., the surface layer). Table 15 provides an overview of the pavement systems defined for various M&R measures.

Table 15. Pavement system elements per type of measure.

Measure type	Structure	Mixture type	Asphalt mixture	Official mixture name	Branch reference mixture equivalence	Common layer thickness (mm)	Notes
Maintenance	Surface layer	BST	EAB	EAB	NA	20	Applied over wheel path (2x0.75m) for rutting
			ZOEAB	ZOEAB	NA	-	20 kg/m2 for ravelling correction
			Retexen	-	-	-	Applied to AC Surf surfaces.
			Planeren	-	-	-	Applied to ZOAB surfaces
Rehabilitation	Surface layer	HMA	AC Surf	AC 16 Surf, AC 11 Surf	1, 2, 3, 4	40-50	
			ZOAB	ZOAB 16	7	50	
			ZOABTW	2L-ZOAB 8 + 2LZOAB 16	10, 11, 12	70	25mm of 2L-ZOAB8 (top-layer) over 45mm of 2L-ZOAB16 (bottom layer)
			ZOABTF	2L-ZOAB 5 + 2LZOAB 16	10, 11, 12	70	20mm of 2L-ZOAB5 (top-layer) over 50mm of 2L-ZOAB16 (bottom-layer)
			DZOAB	DZOAB 16	8, 9	50	
			DGD	DGD	15	30	
			SMA	SMA-NL 11	13, 14	35	
			ZOABDI	ZOAB 8	7	25	
	Binder layer	HMA	AC Bind	AC 22 Bind	5, 6	50-100	

5.2.1.3 PRODUCT CASES

Different product cases or scenarios are defined based on the features of the particular collection of M&R measures under consideration in the MJPV, relative to the physical boundaries that dictate the FU definition (see Section 5.2.1.5) and the system boundaries (see Section 5.2.1.6).

5.2.1.3.1 SYSTEM BOUNDARIES CASES

Nine distinct system boundaries cases were identified, seven for rehabilitation measures and two for maintenance measures. In each situation, a different set of system boundaries is applicable.

Maintenance cases are arguably the most complex. Seven different general system boundaries cases were identified based on the measures' characteristics. Each maintenance case pertains different sets of system boundaries for each layer intervened. The rehabilitation cases are outlined and described in Table 16.

The same strategy is applied to maintenance measures. Two cases were identified, one applicable to BST and the other to surface roughening. The maintenance cases are outlined in Table 17. Module D in maintenance cases would only be relevant if a life extension is granted to the existing pavement system as a result of the maintenance treatment. This feature is not currently considered by the framework.

Table 16. System boundaries cases for rehabilitation.

Case #	Treatment type	Structure components								
		Surface layer / top surface layer			Bottom surface layer			Binder layer		
		In	Out	Modules	In	Out	Modules	In	Out	Modules
1	Functional overlay – surface addition	x	-	A, B	-	-	-	-	-	-
2	Functional overlay –(top) surface replacement	x	x	A B, C, D	-	-	-	-	-	-
3	Functional overlay - top and bottom surface replacement	x	x	A, B, C, D	x	x	A, C, D	-	-	-
4	Structural overlay – binder addition	x	x	A, B, C, D	-	-	-	x	-	A, D
5	Structural overlay - binder addition	x	x	A, B, C, D	x	x	A, C, D	x	-	A, D
6	Structural overlay – binder replacement	x	x	A, B, C, D	-	-	-	x	x	A, C, D
7	Structural overlay – binder replacement	x	x	A, B, C, D	x	x	A, C, D	x	x	A, C, D

Table 17. System boundaries cases for maintenance.

Case	Treatment	Module
8	BST	A, B
9	Surface roughening	B

Note that new cases with an appropriate set of system boundaries must be created in response to new measures which do not fit the system boundaries definition of the cases hereby described.

5.2.1.3.2 PHYSICAL BOUNDARIES CASES

Due to several considerations, the physical boundaries of the pavement system vary across M&R measures, namely the lane application width. Lanes themselves have an actual width of 3.5m, but measures can consider a larger or a smaller width, depending on the VM and treatment type, pavement structure and the road configuration (see Chapter 3.2.3.1). The definition of physical boundary cases supports the subsequent definition of the FU for the analysis. Table 18 and Table 19 display the various physical boundaries cases for M&R, respectively.

Table 18. Physical boundaries cases for rehabilitation.

Cases	VM type	Application width	Road configuration	Overlay type	Application width (m) – Surface layer	Application width (m) – Binder layer
A	LEM	Lane-wide	2 lanes + shoulder	Functional / structural	5	4.3
B	LEM	Lane-wide	3 or more lanes + shoulder	Functional	4	-
C	LEM	Lane-wide	3 or more lanes + shoulder	Structural	4.5	3.6
D	LEM / MM	Carriageway-wide	All	Functional / structural	3.5 x #L (+ shoulder (5m))	3.5 x #L (+ shoulder (5m))

Notes: #L = number of lanes

Four different physical boundaries cases are identified for rehabilitation measures, and three for maintenance measures. Lane-wide LEM rehabilitation measures have slightly larger application widths than the actual lane width, which vary depending on the road configuration and the layer type. For carriageway-wide measures, the application width is the actual width lane times the number of lanes indicated in the road configuration plus hard shoulder or, in other words, the total actual width of the carriageway. The starting carriageway-wide application width is 12m for two lanes plus hard shoulder carriageway (3.5m x 2 + 5m). If the shoulder is not considered, then the application width is merely the actual lane width times the number of lanes. For maintenance measures, the application width is less than the actual lane width, concerning the space between the marking lines. The application of EAB to correct longitudinal ruts is defined rather differently, as it only accounts for the width of the wheel paths where the application of EAB will be localized. Figure 23 illustrates the different physical boundaries cases for the M&R measures.

Table 19. Physical boundaries cases for maintenance.

Cases	VM type	Application width	Road configuration	Maintenance type	Application width (m)	Depth (mm)
E	LEM	Lane-wide	2 or more lanes + shoulder	BST	3.4	-
F	LEM	Lane-wide	2 or more lanes + shoulder	BST	2x0.75	20
G	LEM	Lane-wide	2 or more lanes + shoulder	Surface roughening	3.3	-

5.2.1.4 ANALYSIS PERIOD

The analysis period of pavement LCA studies usually extends over many years and spans over several M&R cycles (Harvey et al., 2016). Considering long analysis periods is helpful to capture the effects of the M&R works on subsequent PM decisions (Harvey et al., 2016) and expects designers and/or contractors to think about the future effects of the choices that they make today. However, in the early stages of PM, M&R is often planned over shorter periods of time, one cycle at a time. Moreover, as longer analysis periods require thinking of cycles and activities that occur far in the future in different socio-technical systems that cannot be easily predicted (Harvey et al., 2016; Saxe et al., 2020). This indicates that LCA studies will typically assume that current technologies and practices will remain relatively constant over time to accommodate long analysis periods (Harvey et al., 2016), introducing an inevitable source of uncertainty to the analysis that cannot be overlooked.

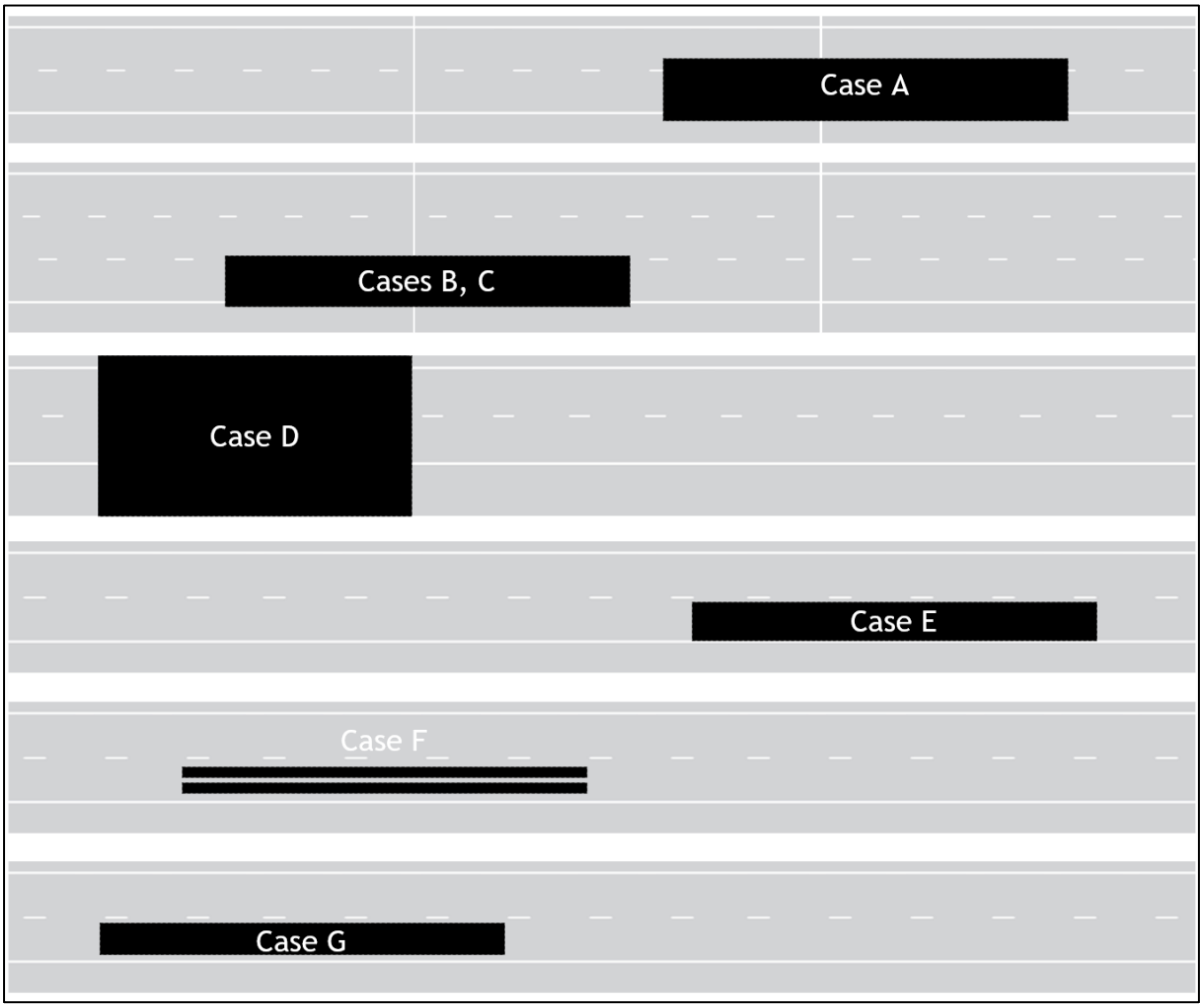

Figure 23. Physical boundaries cases depiction.

ICO plans M&R over 7 years periods. As long-term PM strategies are not part of the assessment, a shorter-term analysis period that covers single M&R cycles is far more appropriate for the context. Therefore, the analysis period considered in this framework corresponds to a single M&R cycle, from the moment that the treatment is applied, to the moment that it is needed again.

In rehabilitation measures, the analysis period pertains to the intended lifespan of the shortest-lived asphalt layer to be restored, making a distinction between right lane or other surfaces. This implies that that the analysis periods for measures that include two layers (i.e., surface and binder, or top and bottom ZOABTW/ZOABTF), the shortest-lived asphalt layer governs the definition of the analysis period, which typically corresponds to the surface layer's life span, hereby referred to as surface life span. The lifespan of the longest-lived asphalt layer, hereby named binder life span (i.e., the analysis period of the binder layer), is only relevant for the definition of the comparative FU (see section 5.2.1.5). For twin layer surface asphalt layers, namely ZOABTW and ZOABTF, two primary analysis periods are defined: surface top, corresponding to the top layer, and surface bottom, corresponding to the bottom layer. Following the same rules, surface top, as the shortest-lived asphalt layer, constitutes the analysis period. Likewise, the surface bottom is only relevant for the definition of the comparative FU. Lane-wide rehabilitation measures should employ the right-lane average lifespan, whereas carriageway-wide rehabilitation measures should either employ the carriageway average lifespan or a combination between the right-lane and other lanes average life spans, for each lane type respectively. This framework recommends resorting to the carriageway average lifespan in the characterization of the analysis period of carriageway-wide measures to simplify the process. However, the choice is ultimately given to the executioner. Table 20 displays the lifespans of different asphalt mixtures and other properties.

Table 20. Expected lifetime and properties of asphalt layers.

Asphalt mixture	Right lane average lifespan (years)	Other lanes average lifespan (years)	Carriageway average lifespan (years)	Density (kg/m3)
AC Surf	12	18	14	2350
AC Bind	45	45	45	2370
ZOAB	10	15	12	2000
DZOAB	11	17	14	2000
ZOABTW, top layer	9	13	10	2000
ZOABTF, top layer	9	13	10	2000
ZOABTW, bottom layer	13	13	13	2100
ZOABTF, bottom layer	13	13	13	2100
SMA	15	20	16	2350
DGD	15	20	16	2300

The analysis period for maintenance measures is inconsequential because they are assessed from cradle-to-laid, and the analysis period makes no difference in their evaluation (see section 5.2.1.6). Note that the NL-PCR suggests adding one or three years of life extension for severe and light ravelling damages, respectively, when applying ZOEAB (+) maintenance measures. Similarly, the application of other maintenance measures may extend the life span of the surface layers by a few years (Van der Pijl, 2022). However, this consideration is only applicable to long-term analysis periods where M&R is assessed as part of the life cycle of pavements, and long-term maintenance strategies are reviewed, which is beyond the scope of the MJPV. Therefore, this feature is excluded from the analysis. Future work may explore the incorporation of life extension implications beyond the original intender service life as part of Module D adapted to maintenance measures.

5.2.1.5 FUNCTIONAL UNIT

Pavement FUs typically consider specifications of the physical dimensions (such as length, width, and number of lanes), along with performance indicators (such as design life) and performance standards (e.g., safety, ride quality, traffic levels, load spectrum, speed characteristics, climatic conditions, etc.). In the LCA framework, three FUs for M&R are defined: default, alternative, and comparative. To ensure an accurate assessment of the pavement system, an individual FU must be defined for both the surface and binder layers in rehabilitation cases where the pavement structure includes both. For composite layers, namely ZOABTW and ZOABTF, an FU for each layer included (top and bottom) must be defined. These requirements apply to all FU types. Consequently, the total impacts of the measure will be obtained by aggregating the results of both the surface(s) and binder layer FUs. The layers that are not affected by the measure are left out of the analysis.

5.2.1.5.1 DEFAULT FU

The default FU is aligned to the conventional FU definition standards (Harvey et al., 2016), often defined in terms of a road carriageway segment of a given length (usually 1km (Harvey et al., 2016)), a specified number of lanes with a given width, certain functional performance characteristics, and over a defined analysis period (Bressi et al., 2022; Chong & Wang, 2017; Heidari et al., 2020; Santos et al., 2022; Vega A. et al., 2020; Zheng et al., 2020).

The default FU employed in this framework is:

> *1km[19] of a lane-/carriageway-wide, maintenance/rehabilitation measure with an X mm depth and a Y m application width applied over a plain and straight carriageway segment with a Z road configuration of an asphalt pavement road located on the main Dutch network.*

By specifying whether a measure is applied lane- or carriageway-wide, it becomes possible to determine whether the measure targets the right lane or all the lanes, which in turn defines the analysis period. Similarly, distinguishing between rehabilitation and maintenance measures provides crucial information about the features of the measure.

The value of X, Y, and Z corresponding to the depth of the asphalt layer(s), the (total) application width of the measure, and the road configuration of the carriageway segment, can be retrieved from the product definition specifications of the measure. If the shoulder is not considered in carriageway-wide measures, the application width will only reflect the width of the traffic lanes contained in the carriageway.

For maintenance measures, the FU is defined differently. Depth is only considered for BST measures that involve the application EAB, where X corresponds to the thickness of the bituminous layer applied (longitudinal rut depth) and indicated by the measure. Maintenance measures that do not involve an application thickness can define X as zero.

The functional performance characteristics of the pavements that belong to the main road network are specified in the OBR (Van der Pijl, 2022).

5.2.1.5.2 ALTERNATIVE FU

The alternative FU is weight-based, and meets the NL-PCR FU standards for a new asphalt layer (Van der Kruk et al., 2022). As most of the LCI input quantities are given per ton of asphalt, the definition of a weight-based FU can facilitate the modelling tasks. Note that the alternative FU is not applicable to surface roughening maintenance measures.

The alternative FU employed in this framework is:

> *1ton of lane-/carriageway-wide, maintenance/rehabilitation measure with an X mm depth and a Y m application width applied over a plain and straight carriageway segment with a Z road configuration of an asphalt pavement road located on the main Dutch network.*

To scale rehabilitation measures from the alternative weight-based FU to the default FU and vice versa, Equation 1 can be employed. 1000 corresponds to the length of the segment in m, X to the depth in m, Y to the application width in m, and density to the asphalt mixture density in ton/m3 (Table 20). For BST maintenance measures, namely ZOEAB (+) and EAB, the conversion is applied differently. Equation 2 and Equation 3 define the conversion formulas to scale them from the alternative weight-based FU to the default FU and vice versa. The formulation of the conversions is fairly similar to that of the rehabilitation measures. The densities/quantities of ZOEAB and EAB are found in Table 21.

Equation 1. From main FU to alternative FU: rehabilitation measures

$$1\ km\ of\ M\&R\ measure = (1000) \times (X) \times (Y) \times (Asphalt\ Density)\ ton\ of\ M\&R\ measure$$

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[19] The MJPV is generally specified for road segments of 100m. The FU can be scaled to this length by dividing over 10.

Equation 2. From main FU to alternative FU: maintenance measures – ZOEAB

$$1\ km\ of\ M\&R\ measure = (1000) \times (Y) \times (ZOEAB(+)\ quantity)\ ton\ of\ M\&R\ measure$$

Equation 3. From main FU to alternative FU: Rehabilitation measures – EAB

$$1\ km\ of\ M\&R\ measure = (1000) \times (X) \times (Y) \times (EAB\ Density)\ ton\ of\ M\&R\ measure$$

Table 21. ZOEAB and EAB quantities.

BST	Density / quantity
ZOEAB (+)	20 kg/m2
EAB	2500 kg/m3

5.2.1.5.3 COMPARATIVE FU

The comparative FU is an area-based FU normalized in function of the analysis period. Evaluating M&R measures in m2 allows for comparisons between, for example, lane-wide and carriageway-wide measures or LEM measures for roads with different road configurations. Furthermore, defining a m2 FU is better aligned with the context of the MJPV, where the application of M&R measures is given in m2. Lastly, the analysis period is used to normalize the results obtained from geometry-related functional units. In other words, dividing the impacts over the analysis period allows to compare measures across different service lives, which are dictated by the lane location and the asphalt mixture of the layer at hand.

To compare the environmental performance of rehabilitation measures, the following normalized FU must be used:

> *1m2 of lane-/carriageway-wide, rehabilitation measure with an X mm depth and a Y m application width applied over a plain and straight carriageway segment with a Z road configuration of an asphalt pavement road located on the main Dutch network over the analysis period.*

For structural overlays, the FU of the surface layer is divided over the surface analysis period, while the FU of the binder layer is divided over the binder analysis period. The same consideration applies for twin layer surface layers. Thereafter, the normalized environmental impacts of the comparative FUs can be aggregated to describe the total of the measure. Comparative LCAs frequently employ year normalized functional units to fairly assess the environmental performance between two or more pavement types (Ziyadi et al., 2017).

The comparative FU of maintenance measures must be treated differently than the comparative FU of rehabilitation measures. Analysis period is not a relevant consideration for the product definition of maintenance measures. As such, the normalized FU for maintenance measures is:

> *1m2 of lane-wide, maintenance measure with an X mm depth and a Y m application width applied over a plain and straight carriageway segment with a Z road configuration of an asphalt pavement road located on the main Dutch network.*

To convert the default FUs to the comparative FUs, Equation 4 and Equation 5 can be used. 1000 correspond to the length of the segment in m, Y to the application width in m, and analysis period to either the surface or binder analysis period, depending on the type of layer, in years.

Equation 4. From default FU to comparative FU: rehabilitation measures.

$$1\ km\ of\ M\&R\ measure = \frac{(Y) \times (1000)}{analysis\ period}\ m2\ of\ M\&R\ measure$$

Equation 5. From default FU to comparative FU: maintenance measures.

$$1\ km\ of\ M\&R\ measure = (Y) \times (1000)\ m2\ of\ M\&R\ measure$$

5.2.1.6 SYSTEM BOUNDARIES AND LIFE-CYCLE STAGES

The system boundaries of the rehabilitation measures are reasonably similar to those of a new asphalt layer as per the NL-PCR (Van der Kruk et al., 2022), with two significant differences. First, the maintenance and repair phases (B2 and B3 (shown in Figure 21), that fit into this document's description of M&R, are not included in the use phase and are instead the focus of the evaluation. Second, the effects of PVI are incorporated into the use phase. Certain attributes that may not provide significant decision support in the later stages of PM can still hold importance when considering the early planning stages (Butt et al., 2015).

Maintenance measures are modelled exclusively in terms of production and construction, or 'cradle-to-laid', and henceforth only include modules A1 – A5, same as in the NL-PCR (Van der Kruk et al., 2022). However, the maintenance treatments included in the MJPV have some specific considerations. For example, BSTs ZOEAB and EAB are cold-mixed on site (CROW, 2016), so module A3 is not applicable to them. Consequently, the transportation of raw materials is generally accounted for in module A4 because it is to the construction site rather than the asphalt plant (see chapter 5.2.2). Furthermore, on-site mixing is considered as a construction activity instead of a production activity (A3) and is modelled along with the treatment execution in module A5. For surface roughening treatments, only module A5 is relevant, as the only activity involved in such processes is the use of specialized machines to roughen the surface layer. Figure 24 provides a comprehensive overview of the M&R system boundaries.

5.2.1.6.1 CUTOFF CRITERIA

5.2.1.6.1.1 CONSTRUCTION PHASE

Some construction related activities, including road markings, sub-base, fences and railings, road signs, drainage and lighting, are excluded from the analysis following the NL-PCR recommendations (Van der Kruk et al., 2022), as their influence over the total environmental impacts is virtually imperceptible (Vos-Effting et al., 2018). Furthermore, traffic implications because of construction works, such as detours and stagnation, are likewise left out from the analysis. Although traffic diversion measures can certainly have considerable network-level effects and result in higher traffic emissions (Lee & Madanat, 2017), their specifics can only be accurately defined as the PM process progresses, at the project-level. Traffic diversion considerations can only be assumed at the early PM stages. Chapter 3.3.5 discusses some of the different assumptions made about traffic diversion. At the stage of the preparation of the MJPV, the execution of M&R works is assumed to occur at night when traffic volumes are lower (Van der Pijl, 2022). As such, the hypothesis is that traffic diversion effects are relatively small and can henceforth be neglected from the analysis. Furthermore, no specific methodology nor tangible examples on how to incorporate traffic diversion in the Dutch PM context have been developed[20], which hinders their widespread incorporation to pavement LCA studies.

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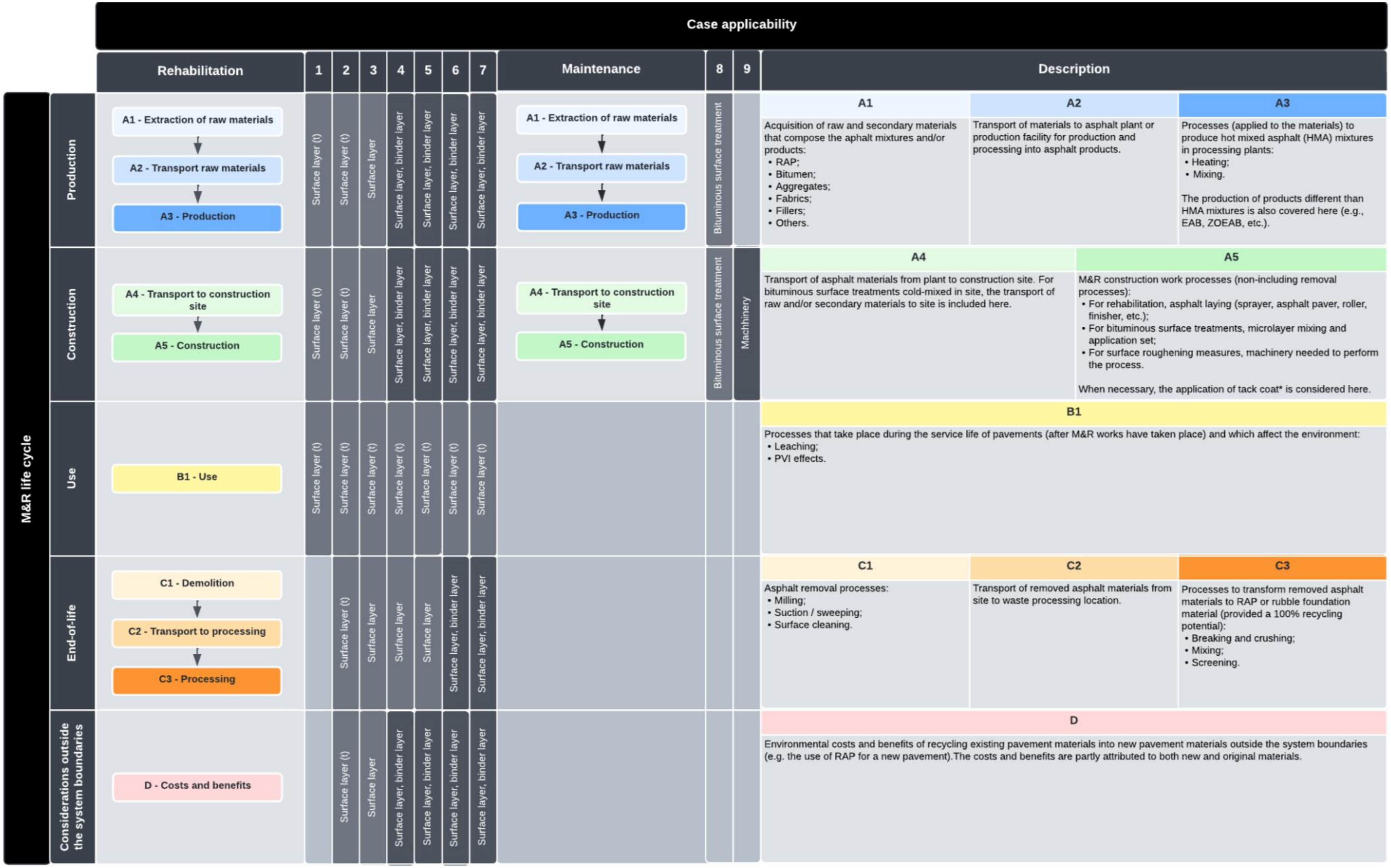
[20] A study performed by Royal HaskoningDHV (Mentink et al., 2020) explored the applicability of various types of traffic models to calculate the emissions associated with traffic diversion measures implemented during M&R works in the Netherlands..



Case applicability

M&R life cycle	Rehabilitation	1	2	3	4	5	6	7	Maintenance	8	9
Production	A1 - Extraction of raw materials A2 - Transport raw materials A3 - Production	Surface layer (t)	Surface layer (t)	Surface layer	Surface layer, binder layer	Surface layer, binder layer	Surface layer, binder layer	Surface layer, binder layer	A1 - Extraction of raw materials A2 - Transport raw materials A3 - Production	Bituminous surface treatment	
Construction	A4 - Transport to construction site A5 - Construction	Surface layer (t)	Surface layer (t)	Surface layer	Surface layer, binder layer	Surface layer, binder layer	Surface layer, binder layer	Surface layer, binder layer	A4 - Transport to construction site A5 - Construction	Bituminous surface treatment	Machhinery
Use	B1 - Use	Surface layer (t)	Surface layer (t)	Surface layer (t)	Surface layer (t)	Surface layer (t)	Surface layer (t)	Surface layer (t)			
End-of-life	C1 - Demolition C2 - Transport to processing C3 - Processing		Surface layer (t)	Surface layer	Surface layer	Surface layer	Surface layer, binder layer	Surface layer, binder layer			
Considerations outside the system boundaries	D - Costs and benefits		Surface layer (t)	Surface layer	Surface layer, binder layer	Surface layer, binder layer	Surface layer, binder layer	Surface layer, binder layer			

Description

A1

Acquisition of raw and secondary materials that compose the aphalt mixtures and/or products:
- RAP;
- Bitumen;
- Aggregates;
- Fabrics;
- Fillers;
- Others.

A2

Transport of materials to asphalt plant or production facility for production and processing into asphalt products.

A3

Processes (applied to the materials) to produce hot mixed asphalt (HMA) mixtures in processing plants:
- Heating;
- Mixing.

The production of products different than HMA mixtures is also covered here (e.g., EAB, ZOEAB, etc.).

A4

Transport of asphalt materials from plant to construction site. For bituminous surface treatments cold-mixed in site, the transport of raw and/or secondary materials to site is included here.

A5

M&R construction work processes (non-including removal processes):
- For rehabilitation, asphalt laying (sprayer, asphalt paver, roller, finisher, etc.);
- For bituminous surface treatments, microlayer mixing and application set;
- For surface roughening measures, machinery needed to perform the process.

When necessary, the application of tack coat* is considered here.

B1

Processes that take place during the service life of pavements (after M&R works have taken place) and which affect the environment:
- Leaching;
- PVI effects.

C1

Asphalt removal processes:
- Milling;
- Suction / sweeping;
- Surface cleaning.

C2

Transport of removed asphalt materials from site to waste processing location.

C3

Processes to transform removed asphalt materials to RAP or rubble foundation material (provided a 100% recycling potential):
- Breaking and crushing;
- Mixing;
- Screening.

D

Environmental costs and benefits of recycling existing pavement materials into new pavement materials outside the system boundaries (e.g. the use of RAP for a new pavement).The costs and benefits are partly attributed to both new and original materials.

Notes: For ZOABTW and ZOABTF, (t) indicates that only the top surface layer is included. When (t) is not indicated, surface layer for these mixture cases refers to both the top and bottom surface layers.
*The life cycle of tack coat is modeled separately. When its application is considered as part of the M&R measure, tack coat should be included as a unit process in module A5.

Figure 24. System boundaries for pavement M&R.

The NL-PCR does not include the application of tack coat, which is the adhesive layer applied between asphalt layers during construction, in the system boundaries of asphalt pavements. Instead, tack coat is considered as a separate product with its own life cycle. However, ICO considers the application of 0.4 km/m2 of tack coat per asphalt layer added or replaced (except for twin layer asphalt overlays where tack coat is only applied under the bottom layer) as part of the construction process for rehabilitation measures. In this framework, it is up to the practitioner to decide whether to include tack coat in the life cycle of pavements. For those who choose to do so, Appendix D provides life cycle and LCI information for modeling tack coats, while Appendix A specifies how the tack coat is applied in the different measures.

5.2.1.6.1.2 USE PHASE

The use phase in this framework only considers PVI and leaching. Albedo, lightning, and other mechanisms which can be allocated to this phase, are left out the framework due to a lack of context representative information to include them. As resources that facilitate their incorporation to the LCA framework become available, such phenomena should be added to this phase.

5.2.1.7 IMPACT CATEGORIES SELECTION

There are numerous impact assessment methods that can be applied in LCA studies to evaluate environmental impacts. In the Netherlands, the impact assessment methods prescribed by the Determination Method were initially harmonized with the CML impact method[21], and from 2021 and onwards, with the PEF methodology. A transition period of 5 years, from 2021 to 2026, has been established to change from CML to PEF. During this period, the environmental impacts of any official LCA study must be calculated with the two methodologies. Table 22 and Table 23 list the different impact categories employed by the CML and PEF methods.

Table 22. Impact categories EN15804 + A1. In accordance with the Determination Method valid until 1 January 2021.

	Impact category	Indicator	Unit
1	Depletion of abiotic raw materials (excluding fossil energy carriers) (abiotic depletion)	ADP -elements	kg Sb-eq.
2	Depletion of fossil energy carriers (abiotic depletion – fossil fuels)	ADP - fuel	kg Sb-eq.
3	Climate change (global warming)	GWP-100j	kg CO2-eq.
4	Ozone layer depletion	ODP	kg CFK-11-eq.
5	Photochemical oxidant formation	POCP	kg C2H4-eq.
6	Acidification	EP	mol SO2-eq.
7	Eutrophication	AP	kg PO4-eq.
8	Human toxicity	HTP	kg 1,4-DCB-eq.
9	Ecotoxicological effects, aquatic (freshwater)	FAETP	kg 1,4-DCB-eq.
10	Ecotoxicological effects, aquatic (marine)	MAETP	kg 1,4-DCB-eq.
11	Ecotoxicological effects, terrestrial	TETP	kg 1,4-DCB-eq.

Table 23. Impact categories EN15804 + A2. In accordance with the Determination Method valid after 1 January 2021.

	Impact category	Indicator	Unit
1	Climate change - total	GWP-total	kg CO2-eq.
2	Climate change - fossil	GWP-fossil	kg CO2-eq.

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[21] The CML characterization factors employed by the Determination method, CML-NMD, are relatively different than the CML-IA baseline. CML-NMD relatively underestimates the environmental impacts of certain categories. The CML-NMD factors can be found on https://milieudatabase.nl/nl/downloads-nmd/downloads-bepalingsmethode/ under the name of ‘Rekenmethode: Karakteristatiefactoren volgens Bepalingsmethode 1.0’

	Impact category	Indicator	Unit
3	Climate change - biogenic	GWP-biogenic	kg CO2-eq.
4	Climate change - land use and land use change	GWP-luluc	kg CO2-eq.
5	Ozone layer depletion	ODP	kg CFC11-eq.
6	Acidification	AP	mol H+-eq.
7	Freshwater eutrophication	EP-freshwater	kg PO4-eq.
8	Seawater eutrophication	EP-seawater	kg N-eq.
9	Land eutrophication	EP-land	mol N-eq.
10	Photochemical ozone formation	POCP	kg NMVOC-eq.
11	Depletion of abiotic raw materials, minerals, and metals	ADP-minerals&metals	kg Sb-eq.
12	Depletion of abiotic raw materials - fossil fuels	ADP-fossil	MJ, net cal. val.
13	Water use	WDP	m3 world eq. deprived
14	Fine particulate emissions	Illness due to PM	Illness incidence
15	Ionizing radiation	Human exposure	kBq U235-eq.
16	Ecotoxicity (freshwater)	CTU ecosystem	CTUe
17	Human toxicity, non-carcinogenic	CTU human	CTUh
18	Human toxicity, carcinogenic	CTU human	CTUh
19	Land-use related impact/soil quality	Soil quality index	Dimensionless

MKI values are currently limited to the CML impact method categories (introduced in Table 12). Since the use of MKI values is a standardized practice in the construction sector, all environmental impacts calculated using the CML impact method must be presented in MKI. If MKI values become available for PEF, all the outcomes derived using the PEF impact method must also be converted to MKI. To ensure that the framework stays up-to-date and aligns with any new approaches that may supersede the use of MKI values, it may require adjustments to be made accordingly. Similarly, if the framework is implemented in contexts with different impact method requirements, it must be appropriately tailored to meet those requirements. In either case, the framework's adaptability guarantees its continued relevance and applicability.

5.2.1.8 DATA REQUIREMENTS

Inventory data is generally classified into two groups: primary (specific) and secondary (generic) data (Harvey et al., 2016). Primary data is collected directly from the specific processes involved in the production of the pavement material or the construction and maintenance of the pavement system. This data provides a more accurate representation of the studied product's life cycle. On the other hand, secondary data are obtained from commercially or publicly available databases, literature, and models, and represent industry averages or distributions. In general, upstream and downstream processes part of the background system may be represented with secondary data, whereas processes under control of the LCA executioner of the foreground system may be represented via primary data.

The NL-PCR (Van der Kruk et al., 2022) delivers a different data classification system and distinguishes between reference, supplier-specific, and project-specific data. Reference data is used to establish a benchmark for the environmental impact of asphalt mixtures representative for the Dutch market without singling a specific provider and provides a standardized basis for LCA studies in the pavement industry, while supplier-specific data represents the environmental impact of a specific asphalt mixture produced by a single supplier that can be used in various projects across the Netherlands. Project-specific data, on the other hand, is used for individual asphalt projects, and considers the location of production and construction, specific equipment data for production, transport and construction, and other project-specific factors. Reference data is primarily used to establish a reference MKI value for projects, while supplier-specific data can be to establish a characteristic value of a specific mixture that is independent of a particular project. Project-specific data is used when applied in specific projects and is necessary to meet client requests and calculate the specific environmental impact of a given asphalt layer. In principle, reference data fits the category of secondary data, whereas supplier-specific and project-specific data fall under the category of primary data.

The data requirements in the PM process vary depending on the stage. The project-level PM stages require detailed and specific data that include primary data. On the other hand, network-level early PM stages require data that cover a broad range of systems and conditions across the network. In such cases, it may be more appropriate to use network-level data sources that can provide a comprehensive view of the entire network (Harvey et al., 2016). Figure 25 schematizes the different data requirements in PM.

This framework advises using secondary reference data in accordance with the NL-PCR to represent pavement systems. To do so, data from the LCA Background Reports for Dutch Asphalt Mixtures (Bak et al., 2022; Schwarz et al., 2020; Vos-Effting et al., 2018) and the NL-PCR (Van der Kruk et al., 2022) can be used. Data sourced from elsewhere, e.g., directly from the industry, can also be used if it is clearly documented and justified. While it is crucial to acknowledge that using secondary data in LCA may lead to uncertainties and inaccuracies in the results, it should be noted that collecting primary supplier-specific or project-specific data may not always be practical or feasible during the early PM stages in the preparation of the MJPV. As the PM process advances and additional information becomes accessible, there will be a transition from using secondary to primary data.

LCI databases, such as ecoinvent and the NMD, are valuable sources of data for the upstream and downstream processes that are beyond the control of the LCA practitioner (Harvey et al., 2016). These databases can be used to provide data for processes that are not feasible to be influenced by the LCA practitioner. However, it is important to note that the background processes can be modified using available information to better represent the context when needed. The LCA practitioner should exercise caution when using secondary data, as it may not fully capture the specific conditions of the system being evaluated, and adjustments may be necessary to improve accuracy.

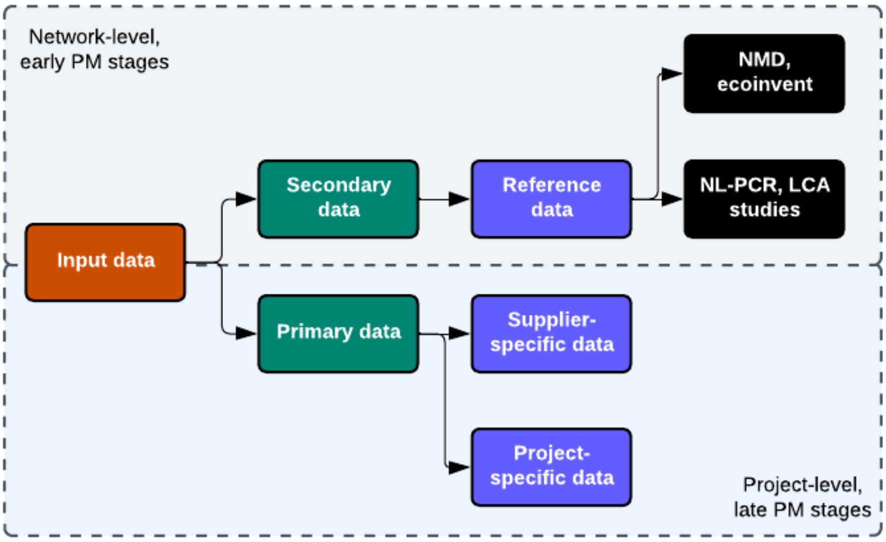

Figure 25. Data requirements in PM.

Data quality assessment requirements are provided as part of the uncertainty analysis framework provided in the following chapter using the ecoinvent pedigree matrix criteria (Weidema et al., 2013), and are aligned with data requirements criteria for pavement LCAs (Harvey et al., 2016): reliability, completeness, temporal correlation, geographical correlation, and further technological correlation.

5.2.2 LIFE CYCLE INVENTORY ANALYSIS

This section provides a comprehensive list of inputs and outputs of all the processes involved in the life cycle of M&R in the context of the MJPV. In rehabilitation measures, pavement systems are characterized with branch reference mixtures (Section 5.2.1.2). The parameter variations per life cycle phase of the asphalt mixtures considered in the MJPV are shown in Figure 26 based on their equivalence with branch reference mixtures. A share of the input parameters is consistent among mixtures or groups of comparable mixtures, while others vary for each mixture. There may also be variations between different versions of the same mixture (e.g., between a regular DZOAB and a 30%RAP DZOAB) that are not captured in the figure. For more information on different mixture scenarios and their parameter implications, please refer to Chapter 5.3.1.2.

Each subsection in this chapter provides empirical quantity[22] input parameters required to model the different life cycle phases of the M&R measures, while the intermediate process flows or process profiles that can be utilized to model these phases are detailed in Section 5.2.3. Additionally, it discloses some methodological decisions that the practitioner may need to make in certain LCI cases.

This section is largely based on reference data sourced from the NL-PCR (Van der Kruk et al., 2022) and different versions of the LCA background report for Dutch branch reference asphalt mixtures (Bak et al., 2022; Schwarz et al., 2020; Vos-Effting et al., 2018). It is important to note that the captured parameters presented within this section should be regularly reviewed and updated to reflect any new information or changes in the available data sources, such as updated NL-PCR versions and recently published LCA background reports. The same applies to the use of this framework in different contexts.

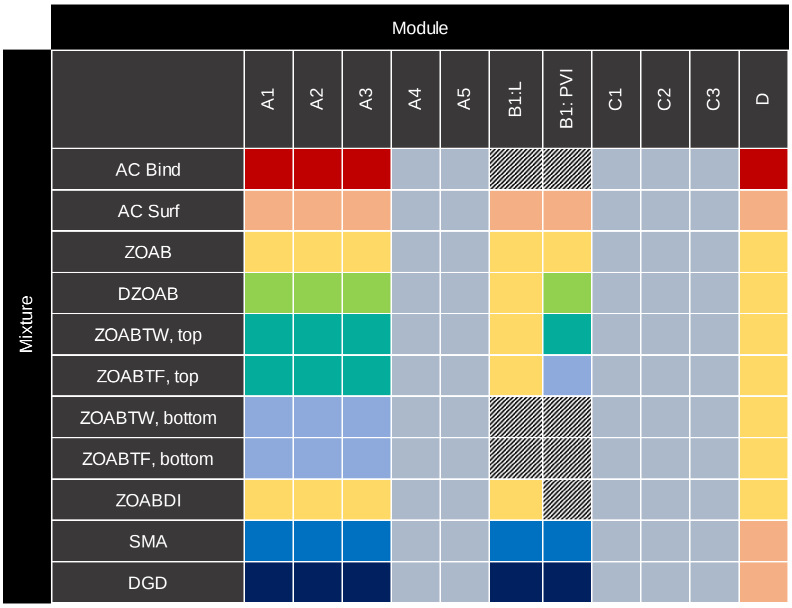

Figure 26. Parameter value variations across asphalt mixtures for rehabilitation measures. Mixtures in each module that are depicted using the same colors indicate that their values are equivalent. Mixtures shown in a particular module with blacked-out patterns denote that the module in question does not apply to the specific mixture being discussed. The variations

5.2.2.1 A1

The extraction and acquisition of raw materials for producing asphalt mixtures and BST are captured in Module A1. Table 24 provides the compositions of various branch reference mixtures required as input for rehabilitation measures during this phase, whereas Table 25 provides the composition information of BSTs.

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[22] Measured quantities that have a known true value, such as electricity consumption, material quantities, distances, etc.

Table 24. Material composition of 1 ton of asphalt mixture. Retrieved from Van der Kruk et al., (2022).

Material (kg/ton)	AC Surf	AC Surf, 30% RAP	AC Surf, modified bitumen	AC Surf, modified bitumen, 30% RAP	AC Bind, 50%PR	AC Bind, modified bitumen, 50% RAP	ZOAB	DZOAB	DZOAB, 30%RAP	ZOABTW and ZOABTF, top layer, modified bitumen	ZOABTW and ZOABTF, bottom layer	ZOABTW and ZOABTF, bottom layer, 30% RAP	SMA 8-11	SMA 8-11, modified bitumen	DGD
Drip-resistant material	-	-	-	-	-	-	-	2	2.1	-	2	2.5	3	3	2.4
Asphalt granulate (RAP)	-	294	-	294	501	501	-	-	300	-	-	277.5	-	-	-
Bitumen 40/60	58	46	-	-	-	-	-	-	-	-	-	-	-	-	-
Bitumen 70/100	-	-	-	-	20	-	45	52	41.2	-	42	35.4	68	-	-
Modified bitumen 70/100	-	-	58	46	-	20	-	-	-	58	-	-	-	68	68
Crushed sand	279	258	279	258	-	-	43	43	34.2	53	5	8.6	75	75	53.9
Own material	16	9	16	9	8	8	-	-	9.4	9	9	7.8	91	91	10
Natural sand	92	-	92	-	192	192	-	-	-	-	-	-	73	73	45.5
Crushed stone 2	506	366	506	366	269	269	-	-	-	-	888	648.8	676	676	750
Crushed stone 3	-	-	-	-	-	-	860	852	586.1	830	-	-	-	-	-
Medium filler	-	-	-	-	-	-	52	51	27	50	54	19.4	-	-	-
Weak filler	49	27	49	27	10	10	-	-	-	-	-	-	14	14	70.7

RAP, which is referred to as asphalt granulate in the Dutch context, is considered a waste flow from other pavement systems, and as a result, it enters the system without any environmental burden, with its impacts accounted for in modules C1-C3. Crushed stone 2 is a type of crushed stone obtained through excavation and breaking of river stones, while crushed stone 3 is obtained from a quarry using explosives.

To the best of the author's knowledge, there is no publicly available specific information regarding the composition of the "+ layer" in ZOEAB (+), except that it is composed of a bitumen emulsion and a rejuvenator, with proportions unknown. However, since the NL-PCR does provide similar information for all other components, it is assumed that the addition of the adhesive layer is not included in the system boundaries of the maintenance measures. This is similar to the case of new asphalt layers. For rehabilitation measures, it’s to the discretion of the practitioner to decide whether to incorporate the adhesive layer in the life cycle modelling of ZOEAB (+) or not.

If the adhesive layer is to be included, the rejuvenator profiles including in the next section together with the contents of Appendix D can be used to model the bitumen emulsion tack coat layer (0.4 kg/m2). If information on the proportions of rejuvenator and bitumen emulsion in ZOEAB (+) is unavailable, the rejuvenator may be excluded from the analysis. However, if such information is available, the framework must be updated to reflect the actual values.

Table 25. Material composition for 1 ton of BST. Retrieved from Van der Kruk et al., (2022). (+) indicates that the use of the given material is only relevant for ZOEAB (+).

Material (kg/ton)	ZOEAB / ZOEAB (+)	EAB
Crushed stone 3	880	880
Bitumen emulsion	100	100
Cement	15	15
Rejuvenator, wax	(+) unknown	-
Rejuvenator, bio-based	(+) unknown	-
Rejuvenator, unspecified	(+) unknown	-

5.2.2.2 A2

Module A2 encompasses the transportation of materials from A1 to the production plant in A3, which may involve various modes of transport such as trucks, inland vessels, sea vessels, or a combination thereof, depending on the origin of the material. Table 26 contains the reference distances associated with the raw and secondary materials of asphalt mixtures. Notably, since most of the asphalt granulate is crushed at the asphalt plant, the transport distance for asphalt granulate in branch reference mixtures is assumed to be zero. The transport distances of rehabilitation measures, namely BST, are given in module A4.

Table 26. Transport distance in km of raw materials for asphalt mixtures. Retrieved from Van der Kruk et al., (2022).

Material	Origin location	Truck (km)	Inland vessel (km)	Sea vessel (km)
Drip-resistant material	Hückelhoven, Germany	177	-	-
Asphalt granulate (RAP)	Asphalt plant	0	-	-
Bitumen 40/60	Netherlands, Belgium, Germany	250	-	-
Bitumen 70/100	Netherlands, Belgium, Germany	250	-	-
Modified bitumen 70/100	Netherlands	150	-	-
Crushed sand	Kehl, Germany	25	660	-
Own material	NA	25	150	-
Natural sand	Netherlands	25	150	-
Crushed stone 2	Kehl, Germany	25	660	-

Crushed stone 3	Bremanger quarry, Norway	25	53	933
Medium filler	Steengroeveweg, Winterswijk	136	-	-
Weak filler	Steengroeveweg, Winterswijk	136	-	-

5.2.2.3 A3

Module A3 encompasses the energy consumption of various asphalt production processes, including the heating of bitumen using electricity, heating using natural gas (for white drum, parallel drum, recipe changes, starts and stops, air warming, and superheating if applicable), and diesel consumption for operating shovels and cranes. The energy consumption values for the branch reference mixtures can be found in Table 27 and the energy content of each energy source is found in Table 28. These values were obtained from the 2022 LCA Background report for Dutch branch reference mixtures (Bak et al., 2022), which follow the NL-PCR guidelines (Van der Kruk et al., 2022) to estimate energy consumption. This method requires either the use of the Energy Allocation (EA) model or a simplified EA model to calculate energy consumption related to the production of asphalt mixtures.

Table 27. Energy consumption per ton of asphalt produced. Based on Bak et al., (2021).

Branch reference asphalt mixture	Natural gas (m3)	Electricity (kWh)	Diesel (L)
AC Surf	8.81	6.57	0.12
AC Surf, 30%RAP	9.18	5.88	0.12
AC Surf, modified bitumen	8.81	6.57	0.12
AC Surf, modified bitumen, 30%RAP	9.18	5.88	0.12
AC Bind, 50%PR	9.27	4.39	0.12
AC Bind, modified bitumen, 50%RAP	9.27	4.39	0.12
ZOAB	7.48	5.82	0.12
DZOAB	7.43	6.23	0.12
DZOAB, 30%RAP	8	5.61	0.12
ZOABTW and ZOABTF, top layer, modified bitumen	7.44	6.57	0.12
ZOABTW and ZOABTF, bottom layer	7.38	5.65	0.12
ZOABTW and ZOABTF, bottom layer, 30%RAP	7.99	5.27	0.12
SMA 8-11	8.02	7.14	0.12
SMA 8-11, modified bitumen	8.02	7.14	0.12
DGD	7.5	7.14	0.12

Table 28. Energy content in MJ of electricity, natural gas and diesel consumption. Retrieved from Van der Kruk et al., (2022).

Energy source	Energy content
Electricity	3.6 MJ/kWh
Natural gas	31.65 MJ/Nm3
Diesel	35.8 MJ/L

Table 29. Emissions to air resulting from the heating production processes. Retrieved from Van der Kruk et al., (2022).

Emissions to air (unspecified)	Quantity (mg/ton)
Benzo(a)pyrene	0.068
Naphthalene	7.293
PAHs	9.639

In addition to the upstream processes emissions, the environmental impact of asphalt production is further exacerbated by the emission of polycyclic hydrocarbons (PAHs) during the heating of materials in the asphalt plants. PAH emissions in the NL-PCR (Van der Kruk et al., 2022) follow a worst-case scenario approach based on the limit value specified in the 'air regulations for asphalt mixing plants' and are defined in a standardized way for all asphalt mixtures. The PAH emissions to consider in module A3 are displayed in Table 29.

5.2.2.4 A4

Module A4 contains the transportation of asphalt mixtures for rehabilitation measures from the asphalt plant in A3 to the construction site in A5, as well as the raw materials for BST in A1 to the construction site where they are cold mixed (A5).

The transport of asphalt mixtures for rehabilitation measures encompasses both the journey to get to the construction site from the asphalt plant and back. The NL-PCR (Van der Kruk et al., 2022) calculates an effective transport distance for the journeys based on the assumption that 70% of the journeys are made with an empty load, while the remaining 30% are made with a full load. As per the guidelines of the Determination Method (Nationale Milieudatabase, 2020), the effective transport distance is defined as 89% of the actual transport distance. For modelling, 75% of the effective distance is based on Euro 5, and the remaining 25%, on Euro 6. Table 30 provides the effective distance specifications to model transport for rehabilitation measures in A4.

Table 30. Transport distance of asphalt mixtures from asphalt plant to site, divided by type of transport. Retrieved from Van der Kruk et al., (2022).

	Distance (t*km)	
Transport type	Total	Effective
Euro 5 (75%)	37.5	33.3
Euro 6 (25%)	12.5	11.1
Total (100%)	50	44.4

According to the NL-PCR, the transportation of raw materials for EAB and ZOEAB (+) should be modelled differently for each case. For ZOEAB (+), Table 31 provides the reference distances that must be used. On the other hand, for EAB, the transportation requirements depend on the size of the project. For small projects (<1500 m2), the transport should be included in Module A2 using, plus an additional 100km per axle in Module A4. For large projects (>1500 m2), transport must be calculated in Module A4 using the standard distances from Table 31, plus an additional 4 km of post-transport per axle. Since there is limited information available during the early PM stages, it is up to the discretion of the executor to determine whether an EAB project is considered small or large. However, it is the recommendation of this framework that transport of the raw materials of EAB is always modelled in A4, regardless of project size, as opposed to the recommendations of the NL-PCR.

Table 31. Transport distance in km of raw materials for BST. Retrieved from Van der Kruk et al., (2022).

Material	Truck (km)	Inland vessel (km)	Sea vessel (km)
Bitumen	89	-	-
Bitumen emulsion	200	-	-
Cement	100	-	-
Emulsifiers	100	-	-
Crushed stone	-	53	933
Rejuvenator, wax	500	-	-
Rejuvenator, bio-based	150	-	-
Rejuvenator, unspecified	150	-	-

5.2.2.5 A5

Module A5 encompasses the construction processes involved in M&R measures. For rehabilitation measures, it includes the fuel consumption required for spreading, laying, and rolling of asphalt.

Processes related to asphalt removal and surface cleaning are assigned to module C1. If tack coat is included as part of the construction activities, a quantity of 0.4kg per m2 of asphalt layer must be considered.

For maintenance measures, A5 includes the fuel consumption of either the machinery required for BST, or the specialized machinery used for surface roughening during retexen and planeren. The definition of A5 in this framework complies in most part with the standards of the NL-PCR rather than the with ICO's view of the construction process (see Chapter 3.3). This is because ICO's assumptions are primarily applicable to cost calculations and not environmental impact calculations.

The fuel consumptions of the machinery for rehabilitation measures are listed in Table 32. They are given in terms of different machinery stage classes and power groups, as well as for different construction rates. The energy content of diesel is given in Table 28[23]. The decision of which construction rate to use is given to the LCA practitioner, but a rate of 1000 ton/day is recommended following the standards of the last LCA branch reference mixtures report (Bak et al., 2022). The emissions associated with the construction processes are given in Table 33. The nitrogen oxides emissions were calculated in function of the contribution of machinery stage class (IIIb or IV) and their power group (in kWh) to the total liters of diesel per construction volume. The emissions that are not listed in Table 33 are modelled based on the respective ecoinvent processes for 'diesel burned in building machine' (Vos-Effting et al., 2018).

Table 32. Energy consumption of machinery employed in rehabilitation measures for construction processes and different construction rates. Retrieved from Van der Kruk et al., (2022).

		Construction rate (ton/day)					
		400		1000		2000	
Machinery stage class and power group		Liters	MJ	Liters	MJ	Liters	MJ
Stage IIIb	18-37 kW	0.02	0.716	-	-	-	-
	37-56 kW	0.17	6.086	0.12	4.296	0.09	3.222
	75-130 kW	0.24	8.592	0.12	4.296	0.03	1.074
	130-560 kW	-	-	-	-	0.08	2.864
Stage IV	18-37 kW	0.01	0.358	-	-	-	-
	37-56 kW	0.06	2.148	0.04	1.432	0.03	1.074
	75-130 kW	0.08	2.864	0.04	1.432	0.01	0.358
	130-560 kW	-	-	-	-	0.03	1.074
Total		0.58	20.76	0.32	11.46	0.27	9.666

Table 33. Emission profiles of asphalt laying sets related to different construction volumes. Particulates >10 µm are calculated as 95% PM2.5 and 5% PM >2.5 & <2.5. Retrieved and adapted from Vos-Effting et al., (2018).

Emissions in g/kWh	Production rate (ton/day)		
	400	1000	2000
Ammonia	8.42E-04	8.42E-04	8.42E-04
Carbon dioxide, fossil	267	267	267
Carbon monoxide, fossil	0.193	0.193	0.193

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[23] Density of diesel is approximately 0.838 kg/l. According to ecoinvent, 0.02340 kg of Diesel produce a MJ. Therefore 0.0279236 l produce 1 MJ, or 35.812002 MJ are produced with 1 L. Other sources claim that the density of petroleum diesel is about 0.85 kg/l – about 15–20% higher than the density of gasoline, which has a density of approximately 0.70–0.75 kg/l. When burnt, diesel typically releases energy to the extent of 37.7–39.1 MJ/l, whereas gasoline releases approximately 34.9 MJ/l (Speight, 2011). Both values are virtually equivalent. To guarantee consistency, the ecoinvent value should be used.

Emissions in g/kWh	Production rate (ton/day)		
Dinitrogen monoxide	0.00216	0.00216	0.00216
Nitrogen oxides	3.00	2.94	2.12
NMVOC	0.0321	0.0321	0.0321
Particulates, <2.5 µm	0.0468	0.0468	0.0468
Particulates, >2.5 µm and <10 µm	0.00246	0.00246	0.00246
Particulates, >10 µm	0.04458	0.04458	0.04458
Sulphur dioxide	0.00168	0.00168	0.00168

The fuel consumptions for maintenance measures are given in Table 34 and Table 35. For BST, the manufacturing process of ZOEAB (+) does not include the heating of the adhesive layer (see section 5.2.1.6.1.1). Alternatively, surface roughening measures are performed with, for example, Unimog machines (Straalbedrijf van Gompel, 2023). The data needed to model the deployment of the Unimog includes information on its fuel consumption, energy use, and emissions during operation.

According to RWS and the service provider reference values, retexen has a surface roughening efficiency of 800 - 850 m/h for a 3.5m lane and requires the deployment of a sweeper/suction car, whereas planeren has a surface roughening efficiency of 1400 - 1700 m/h for a 3.5m lane and requires the deployment of a road surface cleaner.

There are numerous Unimog machines[24] with different specifications, and information about the specific Unimog machine used in these processes, as well as their respective fuel consumption, is lacking. As such, the energy consumption to treat 1 m2 of asphalt surface with planeren and retexen is estimated with the NL-PCR values for ‘other construction equipment’. These values should be adjusted given that specific information regarding the machinery and fuel consumption of surface roughening treatments becomes available.

Table 34. Energy consumption of machinery employed in BST maintenance measures for cold-mixing and construction processes. Retrieved from Van der Kruk et al., (2022).

Equipment	Diesel consumption (l/m2)	
	ZOEAB (+)	EAB
Roller	0.010	0.010
ZOAB road surface cleaner	0.018	0.018
Microlayer set – mixing and laying machine	0.020	0.020
Truck	0.01	0.01

Table 35. Surface roughening machinery. Retrieved from

Surface roughening machine	Retexen (l/m2)	Planeren (l/m2)
Unimog proxy (‘other construction equipment)	0.020	0.020
Sweeper	0.015	-
ZOAB road surface cleaner	-	0.018

5.2.2.6 B

Module B in the context of this framework encompasses the processes that occur during the use phase, including leaching and PVI. The incorporation of leaching is guided by the NL-PCR, while the

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[24] The Unimog 435, for example, has a fuel consumption range of 17.5-19 l/100km to 20-22 l/100km, depending on the model, and it is intended to be a 7.5-ton truck.

development and incorporation of PVI are specific to this framework. Both leaching and PVI are only relevant for surface layers, which are exposed to external elements and vehicular traffic.

5.2.2.6.1 LEACHING

Incorporating leaching into the life cycle assessment of asphalt mixtures is grounded on empirical evidence from leaching tests conducted in 2019 and documented in the NL-PCR (Van der Kruk et al., 2022). The results of these tests, which detail the emissions of different asphalt mixtures to freshwater, are provided in Table 36. However, it is advisable to incorporate leaching into LCA only when there are significant concerns about the pavement materials, which is not always the case since most leaching from standard materials is deposited on the road by vehicles and air rather than originating from the materials themselves (Harvey et al., 2016). Therefore, this framework suggests that practitioners use their judgment in determining whether to include leaching in their studies.

Table 36. Emissions of inorganic substances to freshwater due to leaching during the use phase for different asphalt mixtures. Retrieved from (Bak et al., 2022).

Emission to freshwater (unspecified)	AC Surf (kg/ton)	SMA (kg/ton)	DGD (kg/ton)	ZOAB, DZOAB, ZOABTW, ZOABTF (kg/ton)
Antimony	5.34E-06	7.70E-06	9.18E-06	2.80E-05
Arsenic	2.57E-05	3.70E-05	4.41E-05	1.39E-04
Barium	5.95E-05	8.57E-05	1.02E-04	4.88E-04
Bromide	1.46E-04	2.10E-04	2.50E-04	8.87E-04
Cadmium	8.53E-07	1.23E-06	1.47E-06	4.30E-06
Chloride	6.09E-03	8.77E-03	1.05E-02	7.30E-02
Chromium	1.06E-05	1.52E-05	1.81E-05	8.10E-05
Cobalt	1.41E-05	2.02E-05	2.41E-05	5.14E-05
Copper	1.35E-05	1.94E-05	2.31E-05	6.28E-05
Fluoride	2.76E-04	3.97E-04	4.73E-04	1.60E-03
Lead	2.65E-05	3.82E-05	4.55E-05	1.70E-04
Mercury	2.17E-07	3.12E-07	3.72E-07	3.00E-06
Molybdenum	5.57E-06	8.02E-06	9.56E-06	4.73E-05
Nickel	2.14E-05	3.08E-05	3.68E-05	1.26E-04
Selenium	2.43E-06	3.51E-06	4.18E-06	9.40E-06
Sulphate	6.33E-03	9.12E-03	1.09E-02	1.94E-01
Tin	2.40E-05	3.46E-05	4.13E-05	2.74E-05
Vanadium	2.06E-05	2.97E-05	3.54E-05	2.51E-04
Zinc	6.36E-05	9.16E-05	1.09E-04	3.81E-04

5.2.2.6.2 PVI

The environmental impacts associated with additional fuel consumption due to the deterioration of pavements during the analysis period are determined for each type of vehicle with Equation 1 (Santos et al., 2022),

$$EnvImpRR(t)^i_j = \frac{\Delta FC^j_{RR}(t)}{FE^j} \times EnvImp^j_i \times length$$

Equation 6. Environmental impacts due to extra fuel consumption (Santos et al., 2022).

where $EnvImpRR(t)^i_j$ = environmental impacts of category i produced in year t by vehicle type j due to RR; $\Delta FC^j_{RR}(t)$ = additional fuel consumption due to RR in year t for vehicle type j in l/km obtained from the MIRIAM model (see Table 37); FE^j = fuel efficiency (l/km) of vehicle type j; $EnvImp_i^j$ = environmental impacts of category i corresponding to the service of transport in a vehicle type j for a journey length of 1 km; and $length$ is the length in km of the road pavement section under analysis in km. The fuel efficiency (Table 38) and the environmental impacts of the service of transport are sourced from the ecoinvent database and modified to exclude the upstream impacts attributed to infrastructure (Santos et al., 2022).

Table 37. Additional fuel consumption due to an increase of RR over time for the Dutch main road network for LEM, MM, and average. Lower values, middle values and higher values correspond to LEM, average, and MM respectively.

Mixture	Vehicle type	Service life	Extra Fuel (l/km)	std (l/km)	Distribution	CoV
AC SURF	Passenger car	12	63840.8952	43242.064	Normal	0.68
AC SURF	HDV	12	16282.0298	9673.5623	Normal	0.59
AC SURF	HDV + trailer	12	53859.435	38618.0114	Normal	0.72
AC SURF	Passenger car	18	151173.667	102396.142	Normal	0.68
AC SURF	HDV	18	38555.4455	22906.7572	Normal	0.59
AC SURF	HDV + trailer	18	127537.815	91446.4996	Normal	0.72
AC SURF	Passenger car	14	88169.7027	59720.9659	Normal	0.68
AC SURF	HDV	14	22486.8671	13360.0118	Normal	0.59
AC SURF	HDV + trailer	14	74384.4578	53334.7562	Normal	0.72
ZOAB	Passenger car	10	25099.467	16945.2959	Normal	0.68
ZOAB	HDV	10	6474.8618	3847.2694	Normal	0.59
ZOAB	HDV + trailer	10	21383.1733	15318.6414	Normal	0.72
ZOAB	Passenger car	15	58381.6815	39414.975	Normal	0.68
ZOAB	HDV	15	15060.6114	8948.79785	Normal	0.59
ZOAB	HDV + trailer	15	49737.5347	35631.356	Normal	0.72
ZOAB	Passenger car	12	36516.4909	24653.2224	Normal	0.68
ZOAB	HDV	12	9420.08975	5597.28132	Normal	0.59
ZOAB	HDV + trailer	12	31109.7623	22286.6497	Normal	0.72
DZOAB	Passenger car	11	41718.1536	28233.4058	Normal	0.68
DZOAB	HDV	11	10724.1431	6361.59365	Normal	0.59
DZOAB	HDV + trailer	11	35408.4814	25369.9946	Normal	0.72
DZOAB	Passenger car	17	104447.718	70686.6089	Normal	0.68
DZOAB	HDV	17	26849.517	15927.2135	Normal	0.59
DZOAB	HDV + trailer	17	88650.4977	63517.625	Normal	0.72
DZOAB	Passenger car	14	68967.8382	46675.0514	Normal	0.68
DZOAB	HDV	14	17728.9957	10516.8931	Normal	0.59
DZOAB	HDV + trailer	14	58536.781	41941.3021	Normal	0.72
ZOABTW	Passenger car	9	30963.1983	20818.4243	Normal	0.67
ZOABTW	HDV	9	8116.41687	4817.73023	Normal	0.59
ZOABTW	HDV + trailer	9	26809.9323	19215.0628	Normal	0.72
ZOABTW	Passenger car	13	65896.128	44305.9383	Normal	0.67

Mixture	Vehicle type	Service life	Extra Fuel (l/km)	std (l/km)	Distribution	CoV
ZOABTW	HDV	13	17273.4237	10253.1323	Normal	0.59
ZOABTW	HDV + trailer	13	57057.1137	40893.6515	Normal	0.72
ZOABTW	Passenger car	10	38329.2074	25771.0362	Normal	0.67
ZOABTW	HDV	10	10047.2768	5963.84712	Normal	0.59
ZOABTW	HDV + trailer	10	33187.8975	23786.242	Normal	0.72
ZOABTF	Passenger car	9	75038.478	50728.3714	Normal	0.68
ZOABTF	HDV	9	18636.7792	11138.9008	Normal	0.60
ZOABTF	HDV + trailer	9	61501.5088	44235.7894	Normal	0.72
ZOABTF	Passenger car	13	159697.493	107960.529	Normal	0.68
ZOABTF	HDV	13	39662.9435	23705.8984	Normal	0.60
ZOABTF	HDV + trailer	13	130888.006	94142.9633	Normal	0.72
ZOABTF	Passenger car	10	92889.8027	62796.4284	Normal	0.68
ZOABTF	HDV	10	23070.3872	13788.7964	Normal	0.60
ZOABTF	HDV + trailer	10	76132.4479	54759.2897	Normal	0.72
SMA	Passenger car	15	85156.8289	57603.5342	Normal	0.68
SMA	HDV	15	22087.9617	13123.1307	Normal	0.59
SMA	HDV + trailer	15	72941.3273	52264.4547	Normal	0.72
SMA	Passenger car	20	158948.402	107519.148	Normal	0.68
SMA	HDV	20	41228.0056	24494.8136	Normal	0.59
SMA	HDV + trailer	20	136147.712	97553.5567	Normal	0.72
SMA	Passenger car	16	97759.8562	66128.7332	Normal	0.68
SMA	HDV	16	25356.9325	15065.3258	Normal	0.59
SMA	HDV + trailer	16	83736.4867	59999.4814	Normal	0.72
DGD	Passenger car	15	101969.387	68899.3465	Normal	0.68
DGD	HDV	15	26099.1682	15520.2394	Normal	0.59
DGD	HDV + trailer	15	86128.5646	61754.5159	Normal	0.72
DGD	Passenger car	20	190329.67	128603.204	Normal	0.68
DGD	HDV	20	48715.0723	28969.1065	Normal	0.59
DGD	HDV + trailer	20	160762.183	115267.11	Normal	0.72
DGD	Passenger car	16	117060.637	79096.3014	Normal	0.68
DGD	HDV	16	29961.7889	17817.2014	Normal	0.59
DGD	HDV + trailer	16	98875.4067	70894.0512	Normal	0.72

Table 38. Fuel efficiency (CBS, 2022b).

Vehicle type	Efficiency kg/km	Density	Efficiency l/km
Petrol	0.06207	0.745	0.0833
Diesel	0.0473	0.84	0.0563

The additional fuel consumption values exhibit significant variability, as indicated by their large coefficients of variation. This variation arises from the uncertainty associated with the prediction models for IRI and MPD employed to estimate RR, as well as the input of traffic and speed values into the fuel consumption model. These inputs themselves are influenced by external factors including network segment location and driving patterns. A detailed explanation of how the additional fuel consumption values were calculated can be found in Appendices E and F.

To ensure the accuracy of the PVI analysis during the analysis period, it is important to note that the additional fuel consumption values provided are valid for a 1km section of carriageway in one direction over the surface (top) analysis period. Therefore, this framework suggests incorporating PVI only to carriageway-wide rehabilitation measures, but the executioner has the discretion to choose otherwise. If carriageway-wide rehabilitation is implemented, the given value can be used without modification. Whether the shoulder is considered as part of the carriageway makes no difference in the analysis as PVI only concerns the traffic lanes. However, if the rehabilitation measures are applied lane-wide, the additional fuel consumption values must be scaled to one lane (or to the number of lanes being rehabilitated) by dividing the value by the number of lanes of the carriageway (excluding the shoulder).

Improving PVI input data is crucial for a more accurate pavement LCA. The values listed here can be used as a starting point, but it's important to be aware of their caveats, assumptions, and limitations. Accordingly, certain considerations must be made to enhance the accuracy of these data. Right lanes, for instance, experience higher traffic volume, which can accelerate pavement deterioration and in turn increase fuel consumption. Different road configurations may also influence fuel consumption, with roads featuring more lanes potentially experiencing higher traffic volumes. Similarly, traffic volumes vary across the entire network, making location-specific fuel economy concerns more pressing in some areas than others. Although these factors are captured to some extent in the data distribution, it may be beneficial in to increase the spatial resolution of the PVI network impacts. Therefore, the framework suggests improving PVI models and related data collection and processing to account for these complexities and adjust the framework accordingly. Additionally, the analysis period considerations delivered in Section 5.2.1.4, should be properly reviewed to implement PVI appropriately in both lane- and carriageway-wide measures. It is difficult to define an analysis period that captures the lifespans of the different carriageway lanes while also accounting for the M&R application frequencies of each.

5.2.2.7 C1

Module C1 pertains to the removal of asphalt layers at the construction site. This activity precedes the construction activities detailed in Module A5 but is exclusively recorded in Module C1. To ensure comprehensive fuel consumption calculations, the entire mass of asphalt removed, and the milling, cleaning, and sweeping/suction processes must be considered. Table 39 provides the fuel consumptions values of the machinery employed in C1. The fuel consumption values are categorized based on different machinery stage classes and power groups, as well as different construction (removal) rates. The selection of a specific construction rate is left to the discretion of the LCA practitioner and must match the construction rate selected in module A5.

Table 39. Energy consumption of machinery employed for asphalt removal processes per construction volume. Retrieved from Van der Kruk et al., (2022).

Machinery stage class	Power group	Construction volume (ton/day)					
		400		1000		2000	
		Liters	MJ	Liters	MJ	Liters	MJ
Stage IIIb	130-560 kW	0.25	8.95	0.58	20.76	0.32	11.46
Stage IV	130-560 kW	0.08	2.864	0.19	6.802	0.11	3.938
Total		0.33	11.814	0.77	27.562	0.43	15.398

Table 40 presents the emissions associated with the asphalt removal processes, which are calculated using a methodology like that used for determining the emissions in Module A5.

Table 40. Emission profiles of asphalt removal machinery related to different construction volumes. Particulates >10 µm are calculated as 95% PM2.5 and 5% PM >2.5 & <2.5. Retrieved and adapted from Vos-Effting et al., (2018).)

	Production rate (ton/day)		
Emissions in g/kWh	400	1000	2000
Ammonia	8.42E-04	8.42E-04	8.42E-04
Carbon dioxide, fossil	267	267	267
Carbon monoxide, fossil	0.115	0.115	0.115
Dinitrogen monoxide	0.00216	0.00216	0.00216
Nitrogen oxides	1.39	1.38	1.37
NMVOC	0.0147	0.0147	0.0147
Particulates, <2.5 µm	0.0292	0.0292	0.0292
Particulates, >2.5 µm and <10 µm	0.00154	0.00154	0.00154
Particulates, >10 µm	0.02782	0.02782	0.02782
Sulphur dioxide	0.00168	0.00168	0.00168

5.2.2.8 C2

For the return transport of removed asphalt to processing, the same fixed load factors as in Module A4 are employed, resulting in the same effective distance thereof. For modelling, 75% of the effective distance is based on Euro 5 and the remaining 25%, on Euro 6, same as in module A4. Alternatively, the NL-PCR (Van der Kruk et al., 2022) indicates that instead, 75% of the transport should be based on Euro 6, while the remaining 25%, on electric lorries (see Section 5.2.3 for more information on this matter). Table 41 provides the effective distance specifications for module C2.

Table 41. Transport distance of removed asphalt site to processing plant, divided by type of transport. Adapted from Van der Kruk et al., (2022).

	Distance (t*km)	
Transport type	Total	Effective
Euro 5 (75%)	37.5	33.3
Euro 6 (25%)	12.5	11.1
Total (100%)	50	44.4

5.2.2.9 C3

Module C3 is responsible for accounting for the processing of the asphalt removed in Module C1 into asphalt granulate or RAP. The environmental impacts of road asphalt mixtures are calculated with 100% recycling considered (Van der Kruk et al., 2022). The crushing, mixing, and/or screening processes are viewed as waste processing procedures to render the removed asphalt suitable for recycling. To ensure comprehensive fuel consumption calculations, the minimum fuel consumption required for the crushing, mixing, and/or screening of the removed asphalt must be included in Module C3. Table 42 provides the diesel consumption values associated with the machinery employed in the processing procedures, with the assumption that the processing of asphalt granulate is the same for all types of road asphalts.

Table 42. Diesel consumption for the processing of asphalt granulate. Retrieved from Van der Kruk et al., (2022).

Machine	Diesel consumption (L/ton)	Energy consumption (MJ/ton)
Crane and shovel	0.185	6.623
Breaker	0.185	6.623

Unlike A5 and C1, the emissions specific to this stage couldn't be sourced from available materials. However, their effects cannot be neglected and incorporating them into the analysis must be done when information to do so becomes available.

5.2.2.10 D

Module D requires that all benefits from reuse, recovery, and recycling, as well as any charges incurred due to the loss of secondary materials at the end of the cycle, are accounted for in the analysis.

Asphalt granulate, or RAP, is considered a secondary raw material in its entirety, as 100% of the asphalt processed in Module C3 is recycled. The net output flow of asphalt granulate per ton of asphalt is calculated as 1000 kg minus the mass of asphalt granulate in the mixture's composition, as specified in Module A1. As such, the net output flow considers mixtures that already contain secondary material (asphalt granulate), and thus, the percentage of secondary material in these mixtures cannot be counted as environmental benefits in Module D.

The net output flow of asphalt granulate is then split into two flows, each of which is used for a different application and has its own raw material equivalent. 70% of the output flow is reused in asphalt as asphalt granulate, with the remaining 30% being used as rubble foundation material for unbound road layers and other civil engineering applications. Loss and quality factors are applied to the asphalt granulate flow, to arrive at a final average composition of the raw material equivalents for different types of asphalt granulate (Table 43). The raw material equivalents must match the mixture type defined in module A1, e.g., for a ZOAB mixture, the raw material equivalents corresponding to asphalt granulate from ZOAB must be used. For the rubble foundation material flow, a one-to-one relationship with the raw material equivalent, gravel, is defined.

Table 43. Raw material quantities in kg employed in the definition of raw material equivalents for 1 ton of asphalt granulate. Retrieved from Van der Kruk et al. (2022)

Raw material (kg)	Bind layer asphalt granulate	Surface layer asphalt granulate	
		From SMA and AC Surf	From ZOAB
Bitumen	47	43.2	32.6
Crushed stone / crushed sand	504	529	554
Sand	330	290	175
Filler	92	96	79

Choosing how to fairly capture downstream recycling benefits for both closed- and open-loop recycling processes is a subjective activity that is dependent on the LCA executioner's judgment (Curran, 2013). Consequently, the decision to include Module D in as part of this framework is left to the discretion of the LCA practitioner but it is not recommended as a baseline practice, going against the recommendations of the NL-PCR. There are two key reasons for this. First, the raw material equivalent quantities provided in the NL-PCR are largely based on expert judgments and assumptions, introducing significant uncertainties to the assessment. Second, in the LCA of pavement systems, the secondary RAP materials are already modelled without any environmental burden, as discussed in Section 5.2.2.1. The same can be assumed for the use of rubble foundation materials in the life cycle of other systems. Thus, the inclusion of Module D runs the risk of double counting by including the benefits of asphalt granulate that are already being accounted in A1 for in this and other systems.

5.2.3 PROCESS PROFILES

The NL-PCR (Van der Kruk et al., 2022) largely prescribes the use of the NMD to model the life-cycle processes of pavements. These profiles are predominantly derived from the ecoinvent database. As access to the NMD is restricted, ecoinvent was used as the primary LCI database to establish the system processes.

Some process profiles, such as crushed stone and bitumen, are context-specific and were developed exclusively for the NMD. When public information to model these processes was available (see Overmars, 2020b, 2020a), they were incorporated into the study. In the absence of such information, alternative profiles were chosen to represent the affected processes. The reason why they were chosen is justified in this section. The process maps employed in this research are outlined in Table 44.

The profile to describe Bitumen is sourced from ecoinvent 3.3. The PCR recommends the use of the profile Bitumen, at refinery {RER} from the ESU dataset incorporated into the NMD (Van der Kruk et al., 2022). However, the environmental impact of Bitumen, as expressed in MKI values, demonstrates minimal variability between the ESU and ecoinvent profiles, with an impact of €0.11 for the ESU profile and €0.10 for the ecoinvent profile (Schwarz et al., 2020). Based on these findings, the difference between the profiles is deemed relatively low, justifying why the bitumen profile delivered by ecoinvent was use instead.

The NL-PCR instructs that 25% of the transport in module C2 is modelled with a process based on a lorry powered by green energy (electricity) (Van der Kruk et al., 2022). The required process, however, is not publicly available and is only accessible through the NMD. Consequently, Euro 5 and Euro 6 are used to model transport in module C2 instead. This matches module A4 and follows the LCA methodology of previous versions of LCA background reports for representative Dutch industry reference mixtures (Schwarz et al., 2020; Vos-Effting et al., 2018).

The use of machinery in A5 and C1 is modelled with the (35.8 MJ) Diesel, burned in building machine' ecoinvent process rather than the NMD process maps for fuel given for different stages and power classes. Furthermore, the values of the emissions associated with the operation of machinery in modules A5 and C1 are sourced from the 2018 LCA background report for representative Dutch industry reference mixtures V2.1 (Vos-Effting et al., 2018). For module C3, as well as for module A5 of maintenance measures, the emissions are sourced from the ecoinvent process. If available, the emission profiles prescribed by the NL-PCR, only accessible via the NMD, should be used.

The cement profile used for asphalt emulsion production is obtained from ecoinvent, while the NMD process profile 0172-fab&Cement, CEM I is mandated by the NL-PCR. Regardless, in lack of access to the profile, it is assumed that the ecoinvent process is appropriate for cement in this context.

Table 44. Process map for the processes of this study's LCA framework.

Module	Material/ Process	Process	Empirical quantity source	LCI database source
A1	Drip resistant material	Cellulose fiber, inclusive blowing in {RoW} | production | Cut-off, U (without borax and boric acid)	NL-PCR	ecoinvent 3.3
	Asphalt granulate[1]	Asphalt granulate (free of environmental burden)	NL-PCR	NL-PCR
	Bitumen	Bitumen adhesive compound, hot {GLO} | market for | Cut-off, U	NL-PCR	ecoinvent 3.3
	SBS modified bitumen	SBS modified bitumen	NL-PCR	Overmars (2020) / ecoinvent 3.3
	EVA modified bitumen	EVA modified bitumen	NL-PCR	Overmars (2020) / ecoinvent 3.3
	Crushed sand	Gravel, crushed {RoW} | production | Cut-off U	NL-PCR	ecoinvent 3.3
	Sand	Sand {GLO} | market for | Cut-off, U	NL-PCR	ecoinvent 3.3

Module	Material/ Process	Process	Empirical quantity source	LCI database source
	Own material	Crushed stone from quarry in Europe excluding transport to Netherlands	NL-PCR	Overmars (2020b) / ecoinvent 3.3
	Crushed stone 2	Gravel, crushed {RoW} | production | Cut-off U	NL-PCR	ecoinvent 3.3
	Crushed stone 3	Crushed stone from quarry in Europe excluding transport to Netherlands	NL-PCR	Overmars (2020b) / ecoinvent 3.3
	Medium filler	Combination of: 30% Lime, hydrated, packed {RoW} | market for | Cut-off, U; 70% Lime {GLO} | production, milled, loose | Cut-off, U	NL-PCR	ecoinvent 3.3
	Weak filler	Combination of: 10% Lime, hydrated, packed {RoW} | market for | Cut-off, U; 90% Lime {GLO} | production, milled, loose | Cut-off, U	NL-PCR	ecoinvent 3.3
	Bitumen emulsion	Combination of: 65% Bitumen adhesive compound, hot {GLO} | market for | Cut-off, U; 34% Tap water {RER}|| market for | Cut-off, U; 1% Emulsifier (see below)	NL-PCR	ecoinvent 3.3
	Emulsifier	Esterquat {RER}|market for | Cut-off, U	NL-PCR	ecoinvent 3.3
	Cement	Cement, Portland {Europe without Switzerland} | market for | Cut-off, U	NL-PCR	ecoinvent 3.3
	Rejuvenator, wax	Paraffin {RER} | production | Cut-off, U Consider adding reprocessing.	NL-PCR	ecoinvent 3.3
	Rejuvenator, bio-based	Soybean oil, refined {GLO} | market for | Cut-off, U Consider adding reprocessing.	NL-PCR	ecoinvent 3.3
	Rejuvenator, unspecified	Fatty alcohol {GLO} | market for | Cut-off, U Consider adding reprocessing.	NL-PCR	ecoinvent 3.3
A2	Transport by truck	Transport, freight, lorry, unspecified {GLO} | market for | Cut-off, U	NL-PCR	ecoinvent 3.3
	Transport by inland vessel	Transport, freight, inland waterways, barge {GLO} | market for | Cut-off, U	NL-PCR	ecoinvent 3.3
	Transport by sea vessel	Transport, freight, sea, transoceanic ship {GLO} | market for | Cut-off, U	NL-PCR	ecoinvent 3.3
A3	Electricity	Electricity, low voltage {NL} | Cut-off, U	Bak et al. (2022)	ecoinvent 3.3
	Diesel	Diesel, burned in building machine {GLO} | Cut-off, U	Bak et al. (2022)	ecoinvent 3.3
	Natural gas	Heat, district or industrial, natural gas {Europe without Switzerland} | production, at industrial furnace >100kW | Cut-off, U	Bak et al. (2022)	ecoinvent 3.3

Module	Material/ Process	Process	Empirical quantity source	LCI database source
	Emissions	17mg/ton asphalt of emissions to air/unspecified from which: 56.7% non-carcinogenic PAHs; 42.9% naphthalene; 0.4% benzo(a)pyrene.	NL-PCR	ecoinvent 3.3
A4	Transport	Transport, freight, lorry >32 metric ton, EURO 5 {RER}| Cut-off, U	NL-PCR	ecoinvent 3.3
	Transport	Transport, freight, lorry >32 metric ton, EURO 6 {RER}| Cut-off, U	NL-PCR	ecoinvent 3.3
A5	Machinery: asphalt paving set	Diesel, burned in building machine {GLO} | Cut-off, U (with modified emissions: see Table 33; production of diesel based on Diesel, low sulfur {Europe without Switzerland} | Market for | Cut-off, U)	NL-PCR / Vos-Effting et al., (2018)	ecoinvent 3.3 / Vos-Effting et al., (2018)
	Machinery: BST	Diesel, burned in building machine {GLO} | Cut-off, U	NL-PCR	ecoinvent 3.3
	Machinery: surface roughening	Diesel, burned in building machine {GLO} | Cut-off, U	NL-PCR	ecoinvent 3.3
	Tack coat*	Tack coat life cycle (See Appendix D)	Juffer et al., (2021) / NL-PCR / GPO (2022)	ecoinvent 3.3
B	Leaching emissions	Emissions to water/freshwater: See Table 36.	Bak et al. (2022)	ecoinvent 3.3
	PVI: car	Transport, passenger car, medium size, petrol, EURO 5 {RER}| Cut-off, U (modified to exclude the upstream impacts attributed to infrastructure)	This report	ecoinvent 3.3
	PVI: HDV	Transport, freight, lorry 7.5-16 metric ton, EURO 5 {RER}| Cut-off, U (modified to exclude the upstream impacts attributed to infrastructure)	This report	ecoinvent 3.3
	PVI: HDV + trailer	Transport, freight, lorry 7.5-16 metric ton, EURO 5 {RER}| Cut-off, U (modified to exclude the upstream impacts attributed to infrastructure)	This report	ecoinvent 3.3
C1	Machinery: asphalt removal set	Diesel, burned in building machine {GLO} | Cut-off, U (with modified emissions: see Table 40; production of diesel based on Diesel, low sulfur {Europe without Switzerland} | Market for | Cut-off, U)	NL-PCR / Vos-Effting et al., (2018)	ecoinvent 3.3 / Vos-Effting et al., (2018)
C2	Transport	Transport, freight, lorry >32 metric ton, EURO 5 {RER}| Cut-off, U	NL-PCR	ecoinvent 3.3
	Transport	Transport, freight, lorry >32 metric ton, EURO 6 {RER}| Cut-off, U	NL-PCR	ecoinvent 3.3
C3	Crane and shovel	Diesel, burned in building machine {GLO} | Cut-off, U	NL-PCR	ecoinvent 3.3
	Breaking	Diesel, burned in building machine {GLO} | Cut-off, U	NL-PCR	ecoinvent 3.3
D	Raw material equivalent for	Bitumen adhesive compound, hot {GLO} | market for | Cut-off, U	NL-PCR	ecoinvent 3.3

Module	Material/ Process	Process	Empirical quantity source	LCI database source
	asphalt granulate: bitumen			
	Raw material equivalent for asphalt granulate: SBS modified bitumen	SBS modified bitumen	NL-PCR	Overmars (2020) / ecoinvent 3.3
	Raw material equivalent for asphalt granulate: EVA modified bitumen	EVA modified bitumen	NL-PCR	Overmars (2020) / ecoinvent 3.3
	Raw material equivalent for asphalt granulate: crushed stone / crushed sand	Crushed stone from quarry in Europe excluding transport to Netherlands	NL-PCR	Overmars (2020b) / ecoinvent 3.3
	Raw material equivalent for asphalt granulate: sand	Sand {GLO} | market for | Cut-off, U	NL-PCR	ecoinvent 3.3
	Raw material equivalent for asphalt granulate: filler	Lime {GLO} | production, milled, loose | Cut-off, U	NL-PCR	ecoinvent 3.3
	Raw material equivalent for ruble foundation material	Gravel, round {RoW} | gravel and sand quarry operation | Cut-off U	NL-PCR	ecoinvent 3.3

Notes:
[1] Asphalt granulate (RAP) enters the system free of environmental burden. Module C3 accounts for the environmental impacts of asphalt granulate processing.
* The use of tack coat is not mandatory and can be decided by the practitioner based on their professional judgment and specific project requirements.

5.2.4 LCIA AND INTERPRETATION

The LCIA and interpretation steps of the LCA framework are closely linked to the application of the uncertainty framework, which will be discussed in the following section. Without the application of the uncertainty framework, the LCA framework can only generate deterministic results, which are inadequate for the purpose of the EPMF in its intended context of application.

5.3 UNCERTAINTY FRAMEWORK

The uncertainty module is a framework designed to address the uncertainties associated with the LCA framework. It is the treatment resulting from answering the knowledge question of *how can different sources of uncertainty be incorporated into the EPMF to provide a comprehensive and accurate representation of environmental performance in the early stages of PM?*

Uncertainty analysis is particularly important at the preparation stage of the MJPV, as the early PM stages are fraught with uncertainty. The development of the MJPV heavily relies on numerous assumptions, and most of the data used to estimate its environmental impacts in the LCA framework is based on reference values. As such, the uncertainty module is intrinsically linked to the LCA framework.

The design of the uncertainty framework draws on the literature and methods of uncertainty analysis presented in Chapter 4.3 on uncertainty analysis. Figure 27 outlines the general framework strategy to address uncertainties, with each step further detailed and linked to the LCA framework in the following subsections.

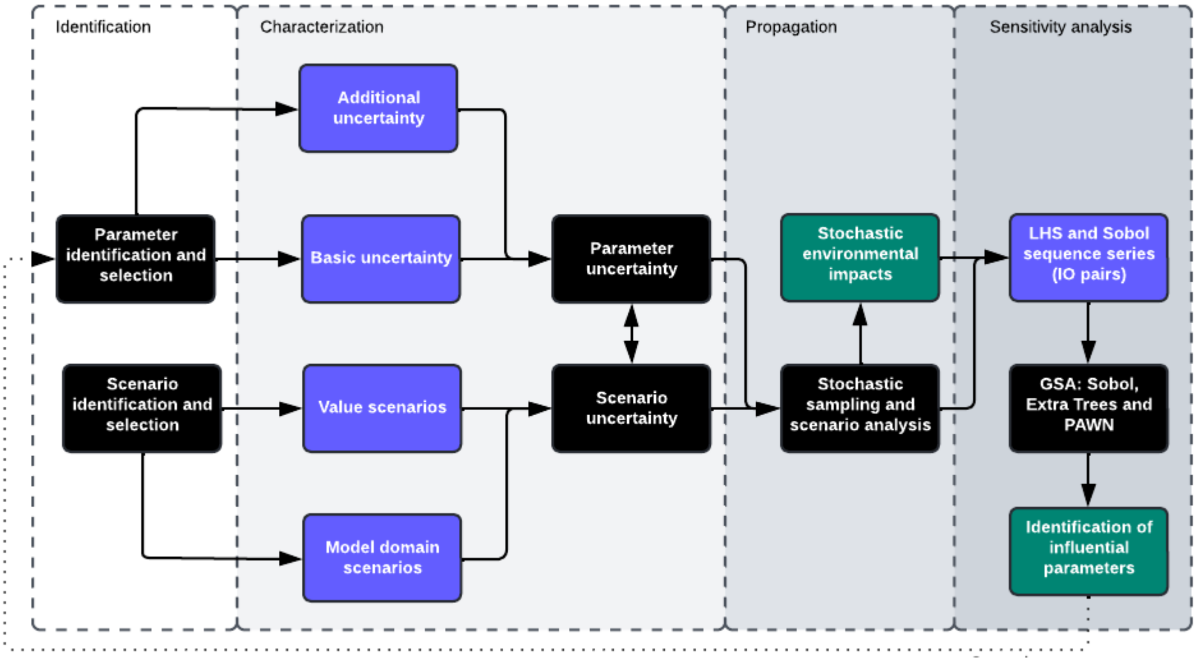

Figure 27. Uncertainty analysis methodology. Black boxes represent the main application steps of the methodology, purple boxes represent intermediate application steps, and the green ones depict the handling of the outcomes of the methodology.

5.3.1 IDENTIFICATION

The initial step in the uncertainty framework is to identify and document all relevant sources and types of uncertainty for the analysis. This framework differentiates between parameter and scenario uncertainty, with model uncertainty classified as one or the other depending on which is better suited to capture it. The uncertainties examined are related to the LCI, as well as the goal and scope (LCIA uncertainties are excluded from the scope). Parameter uncertainty deals with the many unit processes covered in the LCI, while scenario uncertainty pertains to some of the methodological choices made during the goal and scope definition that, among others, may have an influence on the LCI parameters.

The uncertainties presented in this framework are based on the current version of the LCA framework. If any changes or updates are made to the framework that may introduce new sources of uncertainty to the analysis, the uncertainty framework must be modified to reflect the new information. It is important to regularly review and update the uncertainty framework to ensure that it remains relevant and effective in capturing all sources of uncertainty in the analysis.

5.3.1.1 PARAMETER UNCERTAINTY

Parameter uncertainty in the LCI considers the uncertainties in the unit processes of the pavement LCA study, and concerns both the background and foreground systems. Background process uncertainty refers to the uncertainty associated with the data and assumptions used for processes that are not directly under the control of the LCA practitioner whereas foreground process uncertainty, refers to the uncertainty associated with the data and assumptions used for processes that are directly under the control of the LCA practitioner. The focus of the uncertainty framework lies on the parameters that describe the processes of the foreground system displayed in Figure 28. All the parameters that describe the upstream and downstream processes, including the modified emissions of A5 and C1, are left outside the scope of the analysis.

There are two main reasons why this framework only considers foreground-related uncertainties. First, the LCA practitioner has limited control over background processes, which are often sourced from external databases. As a result, foreground uncertainties are more manageable and can be more effectively addressed. Second, while accounting for uncertainty related to the background is to some extent feasible and would result in a more robust analysis, its actual implementation would require addressing a much larger number of uncertain parameters due to the countless inputs that are part of background databases. This would result in a substantial increase in the complexity of the analysis, making it difficult to manage with reasonable computational resources since there is currently a lack of accessible methods to handle the high dimensionality of such an analysis reliably[25] (Igos et al., 2019; Jaxa-Rozen et al., 2021b; Kim et al., 2022).

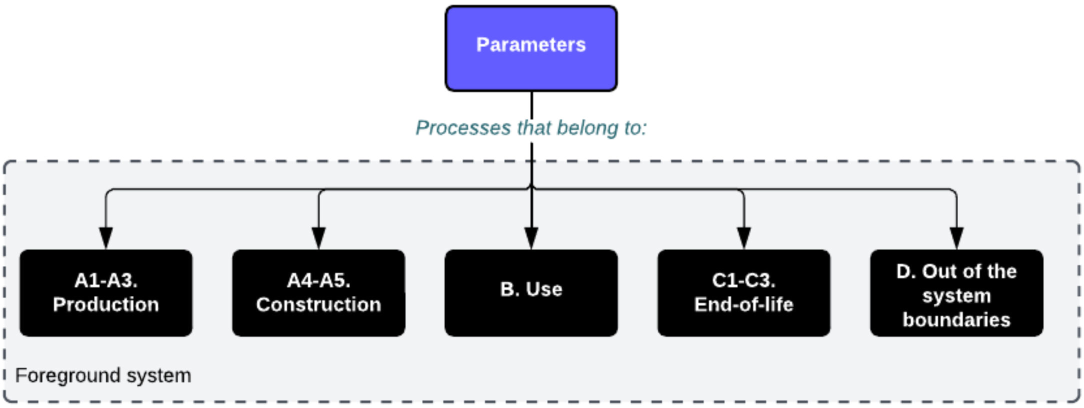

Figure 28. Foreground-related parameters.

5.3.1.2 SCENARIO UNCERTAINTY

Scenario uncertainties arise from methodological choices that may influence the environmental impact calculations. The NL-PCR and the Determination Method dictate how pavement LCA studies should be approached in the Netherlands, which reduce the decision space and, as a result, the number of scenario uncertainties that must be considered in the analysis. Consequently, the scenario space in this project is relatively small, as many parameters, methodological choices, and model formulations are either prescribed by the NL-PCR, such as the reference composition of asphalt mixtures, or carefully defined based on a thorough review of the literature and the socio-technical context of the project.

Despite the standardization of the NL-PCR and the Determination Method, the LCA framework still presents several methodological choices that require the practitioner's input. Furthermore, the previous versions of the EPMF emphasized important scenario considerations, notably the inclusion/exclusion of PVI not solely for impact quantification (when the framework recommends its inclusion in all cases), but also for enhanced sensitivity analysis, as outlined in Section 5.3.4 and Chapter 6.1. Figure 29 displays the different scenario uncertainties identified in the context of the LCA framework, distinguishing between model domain and value scenarios.

Seven model domain scenarios were identified. Three of these scenarios are related to the definition of the FU and the analysis period and pertain to physical and temporal boundaries. They capture the differences between the specifications of the different measures as application width, width type (lane- or carriageway-wide), and analysis period, are all features that vary depending on the measure. The

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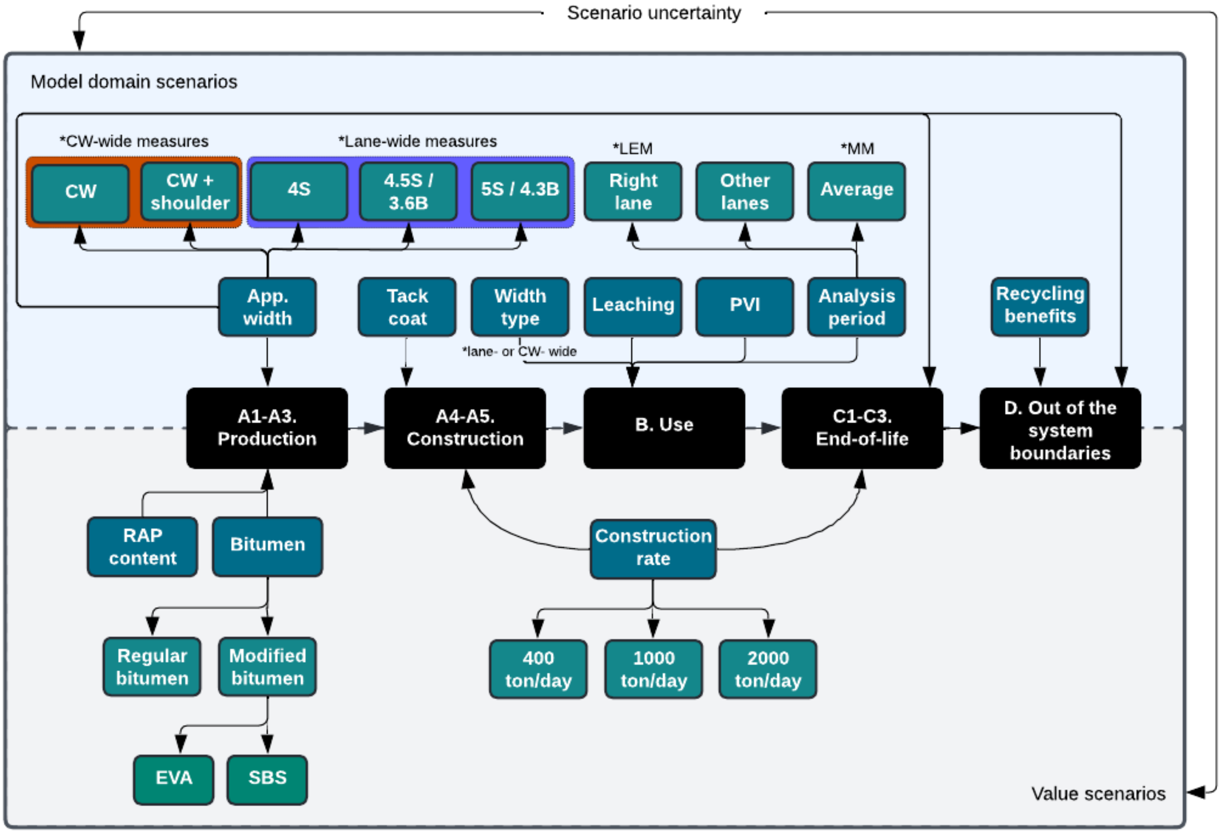
[25] Several methods to deal with background-related uncertainties have been proposed. For examples, refer to Cucurachi et al., (2022); Godoi Bizarro et al., (2020) and Kim et al., (2022). Additionally, plenty of LCA software options, such as SimaPro, Umberto LCA+, OpenLCA, and Brightway2, are equipped to include the uncertainties of the background processes in the assessment (GaBi is not included in this set of options as it is only equipped to manage foreground uncertainties) (Igos et al., 2019), but only so much can be done with them.

remaining four scenarios are related to the inclusion or exclusion of certain system boundaries in the analysis. In addition to model domain scenarios, three value scenarios were identified. These scenarios involve the choice of the RAP content and bitumen that goes into the asphalt mixture, as well as the construction rate. Together, these scenarios provide a range of options for executioners to consider when conducting pavement LCA studies using the LCA framework hereby provided. In practice, not all the scenario uncertainties presented in this framework need to be included in the uncertainty analysis. It is up to the executioner to decide which scenarios to assess. Considering all scenarios as well as parameter uncertainty would make the analysis unfeasible.



Notes: CW = carriageway; S = surface layer; B = binder layer

Figure 29. Scenario identification.

It is worth noting that width type, application width, and analysis period scenarios are only relevant if rehabilitation measures are approached in a more overarching and comprehensive manner, accounting for the uncertainty of addressing the same treatment with different physical and temporal boundaries. Different measures frequently prescribe the same treatment but under different constraints. These scenarios can be dismissed if measures are examined in their entirety rather than grouped by the treatment that they indicate. Figure 30 showcases these scenarios. The width of carriageway-wide measures is also influenced by whether the shoulder is considered part of the pavement system.

For maintenance measures, scenario uncertainty exists in the model domain scenario that pertains to BST with ZOEAB (+) and the decision of whether to include the (+) adhesive layer in the analysis or not. This scenario is analogous to the consideration of tack coat for rehabilitation measures.

5.3.2 CHARACTERIZATION

In this step, the uncertainties identified in the previous step are carefully examined and characterized to gain a better understanding of their potential impact on the LCA results. As LCI data, uncertainty characterization values must be updated as required.

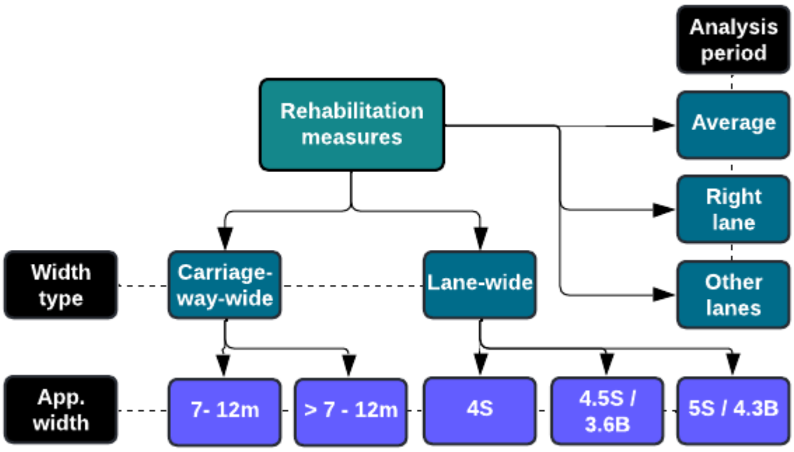


Figure 30. Overarching scenarios. S= Surface layer; B= Binder layer.

5.3.2.1 PARAMETER UNCERTAINTY CHARACTERIZATION

Parameter uncertainty encompasses both basic and additional uncertainties, addressing both issues of variability and data quality.

Additional uncertainty is characterized using the pedigree matrix approach from the ecoinvent method (Weidema et al., 2013). First, the empirical quantity values of each input parameter considered in the analysis are evaluated based on the pedigree matrix shown in Table 45. The scores are thereafter transformed into additional uncertainty values using the factors shown in Table 46.

Table 45. Ecoinvent pedigree matrix to assess the quality of data sources. Retrieved from Weidema et al. (2013).

DQIs / DQI score	1	2	3	4	5 (Default)
Reliability	Verified data based on measurements	Verified data partly based on assumptions or non-verified data based on measurements	Non-verified data partly based on qualified estimates	Qualified estimate (e.g., by industrial expert)	Non-qualified estimate
Completeness	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from only some sites (<<50%) relevant for the market considered or >50% of sites but from shorter periods	Representative data from only one site relevant for the market considered or some sites but from shorter periods	Representativeness unknown or data from a small number of sites and from shorter periods
Temporal correlation	Less than 3 years of difference to the time period of the dataset	Less than 6 years of difference to the time period of the dataset	Less than 10 years of difference to the time period of the dataset	Less than 15 years of difference to the time period of the dataset	Age of data unknown or more than 15 years of difference to the time period of the dataset
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown or distinctly different area (North America instead of Middle East, OECD-Europe instead of Russia)
Further technological correlation	Data from enterprises, processes, and materials under study	Data from processes and materials under study (i.e., identical technology) but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes or materials	Data on related processes on laboratory scale or from different technology

Table 46. Matrix to transform data quality scores into additional uncertainty values. Equivalence of data quality scores to variances of the underlying normal distributions σ^2. Retrieved from Weidema et al. (2013).

Indicator score	1	2	3	4	5
Reliability	0	0.0006	0.002	0.008	0.04
Completeness	0	0.0001	0.0006	0.002	0.008
Temporal correlation	0	0.0002	0.002	0.008	0.04
Geographical correlation	0	2.5 x 10-5	0.0001	0.0006	0.002
Further technological correlation	0	0.0006	0.008	0.04	0.12

In order to characterize basic uncertainty, it is desirable to employ empirical data to construct samples and PDFs. Empirical data can be collected directly, asking contractors and suppliers, or indirectly, via EPDs or bids submitted in previous tenders for M&R projects[26]. For instance, the natural gas consumption variability during A3 can be characterized by gathering data on natural gas consumption from various asphalt providers and fitting a probability distribution that best represents the collected data. From the fitted distribution, mean and variance values can be derived, and basic uncertainty can be defined. However, the process of defining basic uncertainty with empirical values can be time-consuming and resource-intensive and was not feasible for this project. While it is recommended to define basic uncertainty using empirical values whenever possible, this framework relied on default uncertainty values provided by ecoinvent (Weidema et al., 2013) to characterized most of the input parameters. PVI is an exception, as the uncertainty to the input parameters is obtained through the calculation of the extra fuel consumption values and is provided in the LCI of the LCA framework. The ecoinvent default uncertainty values are displayed in Table 47 and should only be used in the absence of empirical data.

Table 47. Ecoinvent default basic uncertainty values (variances of the underlying normal distributions σ^2) for different types of (intermediate and elementary) exchanges. Retrieved from Weidema et al. (2013).

Input/ output group	c	p	a
Demand of:			
Thermal energy, electricity, semi-finished products, working material, waste treatment services	0.0006	0.0006	0.0006
Transport services (tkm)	0.12	0.12	0.12
Infrastructure	0.3	0.3	0.3
Resources:			
Primary energy carriers, metals, salts	0.0006	0.0006	0.0006
Land use, occupation	0.04	0.04	0.002
Land use, transformation	0.12	0.12	0.008
Pollutants emitted to water:			
BOD, COD, DOC, TOC, inorganic compounds (NH4, PO4, NO3, Cl, Na etc.)	-	0.04	-
Individual hydrocarbons, PAH	-	0.3	-
Heavy metals	-	0.65	0.09
Pesticides	-	-	0.04
NO3, PO4	-	-	0.04
Pollutants emitted to soil:			

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[26] In accordance with the green procurement strategy of the RWS (see Chapter 4.5.2), contractors are obligated to submit the LCA results of their proposals. This information is accessible to PPO within the RWS and can be utilized to construct samples and PDFs for the various foreground-related uncertain parameters that describe the life cycle process of pavement M&R Additionally, new tenders present an opportunity to update the samples and, consequently, the uncertainty values of the processes.

Input/ output group	c	p	a
Oil, hydrocarbon total	-	0.04	-
Heavy metals	-	0.04	0.04
Pesticides	-	-	0.033
Pollutants emitted to air:			
CO2	0.0006	0.0006	-
SO2	0.0006	-	-
NMVOC total	0.04	-	-
NOX, N2O	0.04	-	0.3
CH4, NH3	0.04	-	0.008
Individual hydrocarbons	0.04	0.12	-
PM>10	0.04	0.04	-
PM10	0.12	0.12	-
PM2.5	0.3	0.3	-
Polycyclic aromatic hydrocarbons (PAH)	0.3	-	-
CO, heavy metals	0.65	-	-
Inorganic emissions, others	-	0.4	-
Radionuclides (e.g., Radon-222)	-	0.3	-

Notes: c = combustion emissions, p: process emissions, a: agricultural emissions

The ecoinvent method combines additional and basic uncertainty based on the assumption that the random parameters follow lognormal distributions. As such, additional uncertainty values, as well as basic uncertainty values (if defined with default values), are characterized using lognormal distributions. Total parameter uncertainty can be then calculated following Equation 7, where σ^2 is the total variance in the data, σ_b^2 is the basic uncertainty variance, and $\sigma_{n=1:5}^2$ represent the additional uncertainty variances. When basic uncertainty is characterized with empirical values and is represented using distributions other than lognormal, such as the uncertainty regarding the PVI values provided in the LCA framework, the procedure provided by Muller et al., (2016) is adopted to facilitate the numerical integration with additional uncertainty values. For more information on the theory behind the characterization of parameter uncertainty, both in general and specific to the ecoinvent method, refer to Appendix C. The deterministic value of each input parameter, or, in other words, the values assigned in the LCI, are the expected value of the parameters.

Equation 7. Total parameter uncertainty. Retrieved from Weidema et al., 2013).

$$\sigma^2 = \sigma_b^2 + \sum_{n=1}^{5} \sigma_n^2$$

The methodology to characterize additional uncertainty can also be extended to incorporate the uncertainty in the representation of intermediate flows (Gregory et al., 2016). It is common practice to use other relevant unit processes to represent intermediate flows within an inventory when data limitations exist. In such cases, the appropriateness of the data source should be evaluated based on its representation of the intermediate flow[27]. This point is particularly important in cases where the LCI

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[27] The methodology of Yu et al. (2018) provides a useful approach for incorporating parameter uncertainty when using data from multiple sources. This approach involves a stochastic weighted method that evaluates and combines

processes used differ from the ones that should have been employed due to various factors, such as unavailability of the latest process databases or lack of access to the required information.

5.3.2.2 SCENARIO UNCERTAINTY CHARACTERIZATION

The scenario uncertainties considered in the uncertainty analysis can be characterized in two ways. The first approach, recommended by this framework, is to use min/max or alternative scenarios that represent the different options for each choice. Alternatively, the scenario uncertainties can be characterized as discrete choices with equal likelihood of occurrence using binary and uniform probability distributions. Both methods can effectively capture the uncertainties and provide valuable insights for decision-making in the analysis. The choice of approach may depend on the specific context and requirements of the analysis[28].

Table 48. Scenario characterization.

Scenario	Baseline	Alternative
RAP content	Minimum content %	Maximum (larger) contents %
Bitumen	Regular	EVA; SBS
Construction rate	1000 ton/day	400; 2000 ton/day
Width type*	Carriageway-wide	Lane-wide
Application width*	CW=7m (without shoulder) – 12m (with shoulder), L=5m	CW>7m (without shoulder) – 12m (with shoulder), L<5m
Analysis period*	Carriageway average	Right-lane, other lanes
Tack coat	Excluded	Included
Leaching	Excluded	Included
PVI	Included	Excluded
Recycling benefits	Excluded	Included

Notes: CW = carriageway; L = lane.
*Overarching scenarios.

Scenarios can be characterized by defining a baseline scenario representing the preferred option for each choice, while the remaining options are considered as alternative scenarios. The different scenarios are displayed in Table 48. The selection of most of the baseline scenarios, with the exception the overarching scenarios, is explained in the corresponding LCI sections of the LCA framework. For the overarching scenarios, the baseline represents the starting point for carriageway-wide measures with a carriageway of two lanes and a hard shoulder (optional). For lane-wide measures, they represent the least favorable scenario. The width type baseline considers carriageway-wide applications as it is easier to scale down from carriageway-wide to lane-wide. The analysis period is set to the carriageway average due to the considerations laid in Section 5.2.1.4.

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the uncertainty attributed to parameter values that differ significantly across different sources. The method employs a pedigree matrix to assign a DQI score to each source, which is used to calculate probability functions. These probability functions are then weighted based on different criteria, and a Monte Carlo simulation is performed to estimate the probability function of the value. This approach is particularly useful when the processes used for modelling deviate from the ideal, such as when access to the necessary process databases is limited or when working with older versions of such databases.

[28] The decision to characterize scenario uncertainty with scenarios as opposed to probability distributions stems from the fact that incorporating scenario uncertainty as a probability distribution could make it difficult to attribute the uncertainties in the outcomes to either parameter or scenario uncertainty. Additionally, the impacts of different scenario options may be lost if they are input as probability distributions. For instance, bitumen can be defined in three ways, each with its own parameter uncertainty value. If scenario uncertainty is characterized with uniform distributions, the uncertainty range attributed to bitumen would increase, making it difficult to visualize the impacts of different types of bitumen in addition to distinguishing the effects of parameter uncertainty.

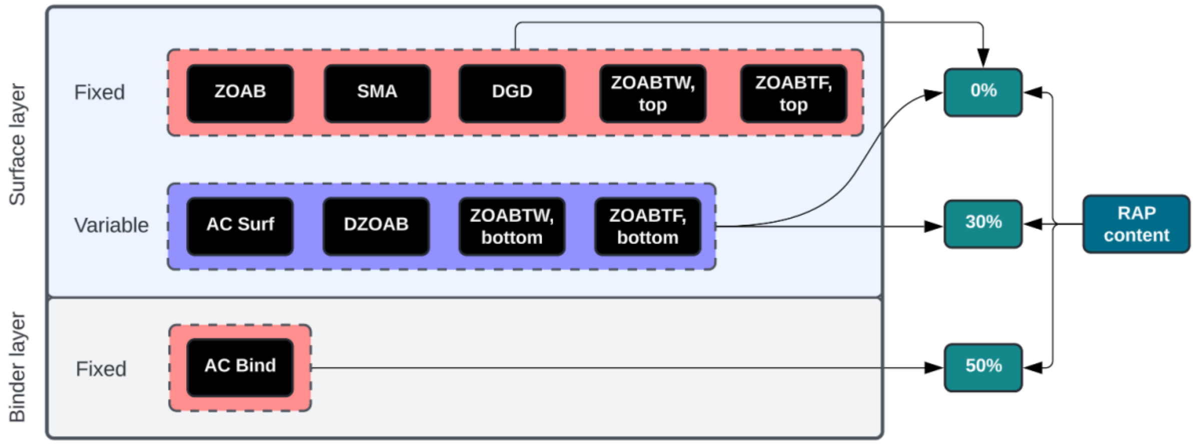
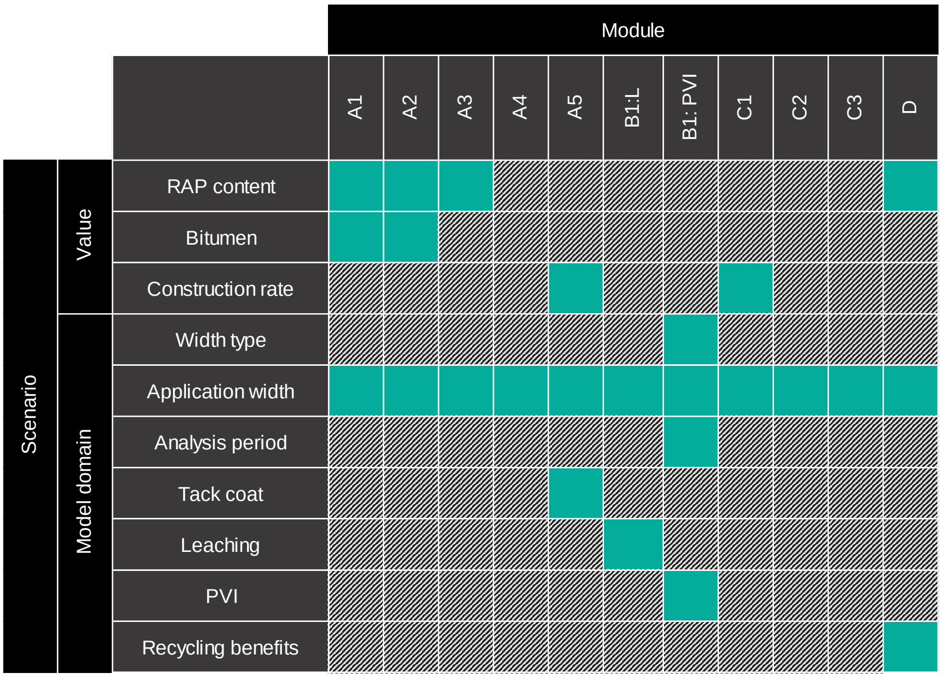


Figure 31. RAP content scenarios for branch reference mixtures.

For value scenarios, which are based on the different versions of asphalt mixtures that are part of the branch reference mixtures, construction rate and bitumen selection scenarios are applicable to all mixtures, even if only a few branch reference mixtures consider modified bitumen in their composition (Van der Kruk et al., 2022), and 1000 ton/day is specified as the standard construction rate (Bak et al., 2022). However, RAP content must be treated differently, as only a few branch reference mixtures consider different RAP contents versions for specific mixtures and can provide the mixture compositions necessary to account for this uncertainty, namely AC Surf, DZOAB, and the bottom layers of ZOABTW/ZOABTF. Figure 31 schematizes the different mixtures and their possible RAP contents based on the branch reference mixtures definition. If new information about the RAP content of mixtures becomes available, the framework must be updated.



			Module										
			A1	A2	A3	A4	A5	B1:L	B1: PVI	C1	C2	C3	D
Scenario	Value	RAP content	🟩	🟩	🟩	▨	▨	▨	▨	▨	▨	▨	🟩
		Bitumen	🟩	🟩	▨	▨	▨	▨	▨	▨	▨	▨	▨
		Construction rate	▨	▨	▨	▨	🟩	▨	▨	🟩	▨	▨	▨
	Model domain	Width type	▨	▨	▨	▨	▨	▨	🟩	▨	▨	▨	▨
		Application width	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
		Analysis period	▨	▨	▨	▨	▨	▨	🟩	▨	▨	▨	▨
		Tack coat	▨	▨	▨	▨	🟩	▨	▨	▨	▨	▨	▨
		Leaching	▨	▨	▨	▨	▨	🟩	▨	▨	▨	▨	▨
		PVI	▨	▨	▨	▨	▨	▨	🟩	▨	▨	▨	▨
		Recycling benefits	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	🟩

Figure 32. Impact of scenario variations on parameters of life cycle processes. Blue cells indicate that corresponding scenario variations affects the parameters defined in the processes contained within the corresponding module.

Scenarios can be combined as desirable, if the implications on the input are clear, as the implementation of each scenario variation has important implications for the LCI parameters of the relevant life cycle processes. Figure 29 shows which life cycle phases are affected by the variations. A scenario combination matrix can be built to keep track of the possible scenario combinations based on the scenario uncertainties selected for the analysis.

5.3.3 PROPAGATION

The propagation of the uncertainty to the results is performed using stochastic sampling and scenario analysis. Stochastic sampling is employed to evaluate the effect of parameter uncertainty, while scenario analysis is employed to evaluate the effect of changing scenarios.

The framework uses two types of stochastic sampling methods: LHS and Sobol sampling. LHS is the default method used in the framework to reduce computational time. This framework recommends a minimum of 12,000 samples for LHS following the methodology of Jaxa-Rozen et al., (2021) and provided that the sensitivity analysis method is adequate for a relatively small number of samples (i.e., Extra Trees and PAWN, see next section). As such, this framework recommends performing LHS with a minimum of 12,000 samples. Sobol sampling, on the other hand, is used to facilitate variance-based GSA in the next step. As previously mentioned, this method is computationally expensive and requires a minimum sample size of $N=n(k+2)$ for first order indices and $N=n(2k+2)$ for higher order indices, where n is the baseline sample size, and k the number of input parameters. This framework recommends defining an n of 2,500 samples for Sobol sampling to ensure convergence following the work Jaxa-Rozen et al., (2021).

The approach used to perform scenario analysis is to run the stochastic model (either LHS or Sobol sampling) with the different scenarios that have been characterized. All the input parameters assigned to each scenario are considered, including materials, transport, additional vehicle fuel consumption, and energy consumption for production, construction, and end-of-life. Therefore, each scenario needs to be sampled separately with its own input values. Note that this consideration is applicable to each scenario combination. This step has as outcome the stochastic environmental impacts of the measure and scenario examined.

5.3.4 SENSITIVITY ANALYSIS

Three GSA techniques are suggested by the uncertainty framework: Sobol (Saltelli et al., 2010; Sobol, 2001), Extra Trees (Geurts et al., 2006) and PAWN (Pianosi & Wagener, 2015). This makes for a more robust analysis, provides opportunities to implement the most adequate option for the context, and accounts for potential differences in the output distributions. The different GSA methods work with input-output pairs, which refer to the combination of input values (sampled parameters) and corresponding output values (stochastic environmental impacts) generated by the LCA model during the uncertainty propagation step.

Sobol can be performed for low dimensionality input spaces and when improved accuracy is sought, or when understanding the relationship between inputs is of relevance. $N=n(k+2)$ samples are required for first order indices, and $N=n(2k+2)$ for higher order indices, with n a baseline sample size, and k the number of input parameters. Extra Trees can be employed when resources are limited or for high dimensionality input spaces, as their results can accurately approximate those obtained with Sobol total indices at a fraction of the computational cost. PAWN should be employed when the environmental impacts distribution is highly skewed, or alongside Extra Trees when replacing Sobol to cross-validate the results. It is suggested that Extra Trees and PAWN are applied to a minimum of 12,000 LHS simulations, based on the work of Jaxa-Rozen et al., (2021b).

The information obtained via this step can be used to identify the key sources of uncertainty in the LCA results, prioritize which aspects should be addressed, and focus the efforts on improving data, refining the model, or adjusting methodological choices to reduce the overall uncertainty in the LCA results.

It is important to note that a single parameter can account for a significant portion of the uncertainty in the results, potentially limiting the practitioner's ability to evaluate the impact of other parameters in the analysis. his situation may arise when the parameter represents a process that significantly contributes to environmental impacts, exhibits large uncertainty values, or a combination of both. To address this, a model domain scenario can be created by excluding the highly uncertain parameter from the analysis, allowing for the evaluation of the remaining parameters' contributions to uncertainty. In the context of this framework, PVI is treated as such a scenario, as it is presumed to have a dominant influence on environmental impact results and has fuel consumption values that exhibit significant spreads and reflect high uncertainty.

5.3.4.1 SCREENING

The uncertainty framework includes an optional step called screening, which aims to reduce the complexity of the input space and improve the accuracy of the results through an iterative uncertainty analysis. This step is useful in, for example, preparing for a higher order Sobol GSA. To determine which processes to include in the analysis, a working subset that contains the most critical processes for the study must be defined, and evidence for their inclusion should be provided. However, this process is not straightforward, and arbitrary choices may introduce bias and uncertainty into the study. Therefore, GSA techniques are recommended to soundly identify the processes that contribute the most to the uncertainty on the results and streamline the process.

In the screening step, it is recommended to use low computational cost GSA techniques. This framework suggests a combination of Extra Trees and PAWN to perform screening (Jaxa-Rozen et al., 2021b). The most influential parameters can be identified either by ranking, such as identifying the 5 most uncertain processes, or by contribution, such as identifying processes that contribute to 95% of the uncertainty on the results. Selecting influential inputs by contribution is preferred, as this technique has been used to streamline LCA (Haanstra & Gelpke, 2019), albeit not in this context.

5.3.5 COMMUNICATION

The use of raincloud plots (Allen et al., 2019) should be considered for presenting graphical representations of the stochastic environmental impacts. A raincloud plot is a powerful and user-friendly method for visualizing intricate datasets. This plot combines key features of a box plot, half violin plot, and scatter plot to effectively convey the shape, density, and spread of the data. By presenting a comprehensive overview of statistical information, raincloud plots are transparent and informative. Overall, the use of rain cloud plots can greatly enhance the clarity and accessibility of stochastic environmental impact data visualization.

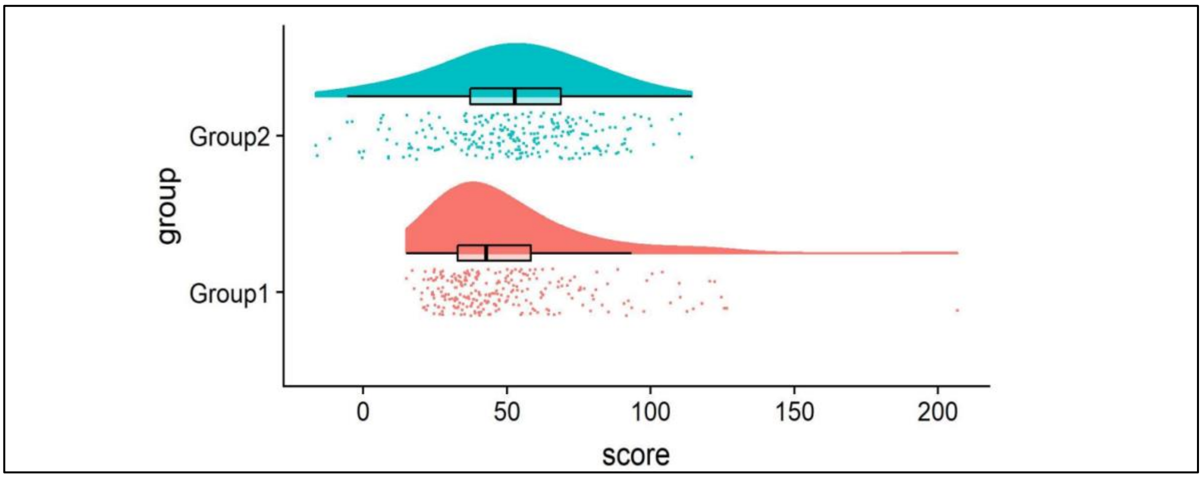


Figure 33. Example raincloud plot. The raincloud plot combines an illustration of data distribution (the ‘cloud’), with jittered raw data (the ‘rain’). This can further be supplemented by adding boxplots or other standard measures of central tendency and error. Retrieved from Allen et al., (2019).

Additionally, it is required to report the mean and median values of the data, as well as the spread, which can be represented by the standard deviation if the outcome distribution follows a normal distribution. Alternatively, if the results don't follow a normal distribution, the spread of the results must be reported with a more fitting measure of spread (e.g., geometric standard deviation95 for lognormal distributions). Furthermore, the ranges of the data, represented by minimum and maximum values, and percentile values, i.e., P2.5 and P97.5, must also be reported.

6 VALIDATION

Validation is a crucial part of the design science approach, and in this project, it is essential to ensure that the EPMF meets the stakeholder goals and requirements. To this end, the following knowledge questions have guided the validation process:

1. *How can the EPMF be validated to ensure that it produces the intended outcomes and meets the stakeholder goals and requirements?*

Validation of the EPMF was conducted by ensuring that it aligned with the stakeholder requirements and expectations and produced the expected outcomes. This was achieved by regular feedback meetings with ICO and UT, as well as interviews and a focus group. Feedback from stakeholders was methodically collected and analyzed and incorporated into the design of the EPMF to better serve their goals and requirements.

2. *What are appropriate strategies for evaluating the effectiveness of the EPMF on ICO's environmental performance in the early stages of PM?*

The effectiveness of the EPMF was evaluated by conducting a case study and testing the results obtained. The case study involved applying the EPMF to a specific rehabilitation measure. To assess the performance of the LCA framework, the deterministic results obtained via the LCA framework were compared against those found in the latest available LCA study of the branch asphalt reference mixtures (Bak et al., 2022). Furthermore, the EPMF was validated through the careful review of the calculation methods and input data, and the results obtained through its application. Additionally, the qualitative assessment of the EPMF against the design requirements established in the early stages of the project was used to evaluate its effectiveness.

3. *How can the EPMF be refined and improved based on validation feedback results to better serve the stakeholder goals and requirements?*

Refinement and improvement of the EPMF were based on feedback from stakeholders and experts collected during the feedback meetings, interviews, and focus group, as well as from the early findings of the case study. The feedback and findings were analyzed and incorporated into the design of the EPMF to better serve the stakeholder goals and requirements. This iterative process of refinement and improvement continued throughout the design and validation phases of the project, ensuring that the EPMF met the stakeholder requirements and expectations.

In summary, the validation was comprehensive and incorporated multiple methods, ensuring that the EPMF met the requirements and expectations of stakeholders, provided accurate and reliable results, and was refined and improved based on feedback and validation results. The following sections further detail the strategies and findings of the case study, interviews and focus group, as well as a verification of the accuracy and fulfillment of the design requirements.

6.1 CASE STUDY: QAN0331

QAN0331 is a MM rehabilitation measure that prescribes a functional overlay with 50mm of DZOAB in and 50mm of ZOAB out. Table 49 presents the product definition information of the measure examined. The pavement structure only includes the surface layer, and the pavement materials involved are DZOAB and ZOAB. The shoulder is not considered as part of the analysis, and the analysis period is set as the carriageway average life span following the recommendations of the framework. If required, these considerations can be modified in the scenario definition of the uncertainty analysis.

The default FU is defined as:

> *1km of a carriageway-wide, rehabilitation measure with a 50 mm depth and a 10.5 m application width applied over a plain and straight carriageway segment with a 3 lanes + shoulder road configuration of an asphalt pavement road located on the main Dutch network*

As the pavement structure only comprises the surface layer, only one FU (of each kind) is required to assess the pavement system. The alternative and comparative FU can be defined based on the default FU and the product definition information.

Table 49. QAN0331 product definition information.

Rehabilitation measure information						
RWS code	QAN0331					
Type (LEM or MM)	MM					
Width (lane- or carriageway-wide)	Carriageway-wide					
Road configuration	3 lanes + shoulder					
Carriageway width with shoulder (m)	15.5					
Carriageway width without shoulder (m)	10.5					
Overlay type	Functional					
Asphalt layers	Surface (top)		Surface (bottom)		Binder	
Layer in/out	In	Out	In	Out	In	Out
Mixture	DZOAB	ZOAB	-	-	-	-
Thickness (mm)	50	50	-	-	-	-
Lane application width	3.5	3.5	-	-	-	-
Total measure width	10.5	10.5	-	-	-	-
Right lane average lifespan (years)	11	11	-	-	-	-
Other lanes average lifespan (years)	17	17	-	-	-	-
Carriageway average lifespan (years)	14	14	-	-	-	-
Density (kg/m3)	2000	2000	-	-	-	-
Area (for 1km of measure) (m2)	10500	10500	-	-	-	-
Volume (for 1km of measure) (m3)	525	525	-	-	-	-
Weight (for 1km of measure) (ton)	1050	1050	-	-	-	-
Tack coat layers (for 1km of measure) (#)	1	1	-	-	-	-
Tack coat total quantity (0.4 kg/m2) (ton)	4.2	4.2	-	-	-	-
Analysis period	Carriage-way	Carriage-way	-	-	-	-
Maintenance measure information						
RWS code	-					
Type	-					
Treatment	-					
Surface layer type	-					
Surface layer age (years)	-					
Lane application width	-					
Area (for 1km of measure)	-					
Weight (for 1km of measure) (ton)	-					
Life extension (years)	-					

The pavement system is modelled according to the guidelines of the LCA framework of the EPMF, using the software OpenLCA and the LCI background database ecoinvent 3.3. The methodological choices that are needed to conduct the LCA were defined based on the recommendations of the EPMF for baseline scenarios. The environmental impacts are defined using the CML impact method only given that the PEF impact categories were not provided in the background database.

Two scenario variations of interest are incorporated into the analysis, RAP content and PVI. RAP content scenarios explore the difference in environmental impacts when RAP materials are incorporated into the mixture, whereas PVI scenarios facilitate a more salient and illustrative uncertainty analysis. The remaining scenarios were excluded to keep the analysis tasks manageable. Table 50 presents the scenario characterization values of this study, and Table 51 displays the different scenario combinations based on the possible scenario variations.

Table 50. QAN0331 scenario characterization.

Scenario	Baseline	Alternative
RAP content	0%	30%
Bitumen	Regular	-
Construction rate	1000 ton/day	-
Width type*	Carriageway-wide	-
Application width*	CW = 10.5 m (without shoulder)	-
Analysis period*	Carriageway average	-
Tack coat	Excluded	-
Leaching	Excluded	-
PVI	Included	Excluded
Recycling benefits	Excluded	-

Notes: CW = carriageway.
*Overarching scenarios.

Table 51. QAN0331 scenario combination matrix.

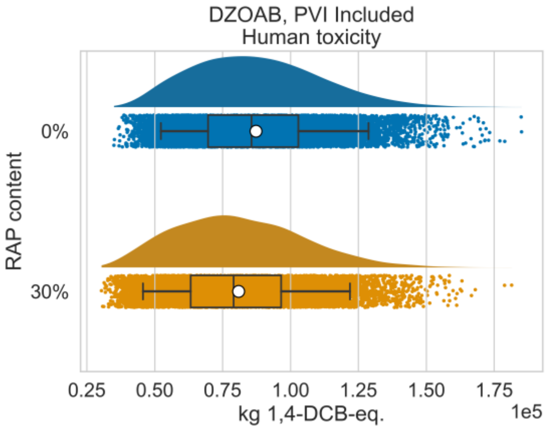
Scenarios	DZOAB 0% RAP	DZOAB 30%RAP
PVI included	PVI included, DZOAB 0% RAP	PVI included, DZOAB 30%RAP
PVI excluded	PVI excluded, DZOAB 0% RAP	PVI excluded, DZOAB 30%RAP

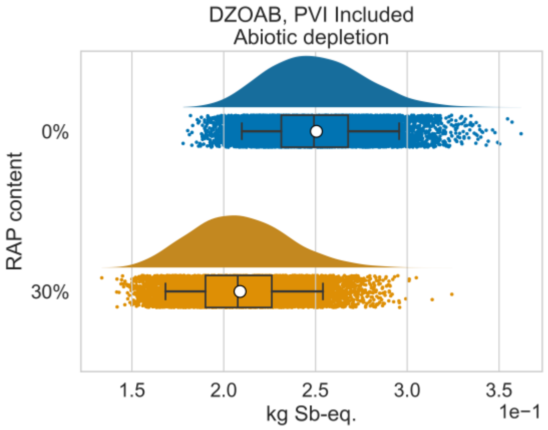
Parameter uncertainty is defined and characterized following the guidelines of the uncertainty framework. All foreground processes included in the analysis related to the different scenarios are considered. Table 52 presents the parameter uncertainty breakdown for the baseline and alternative RAP scenarios, where 25 and 29 uncertain parameters were identified, respectively. The A2 distance for asphalt granulate in the alternative scenario is not considered as an uncertain parameter since its value corresponds to zero. Lower and upper bounds for the extra fuel consumption values (see Appendix E) are provided to truncate the normal distributions that characterize PVI, thus preventing the generation of negative values and extreme outliers. For scenarios excluding PVI, the parameters representing module B1-PVI can be ignored and only 22 and 26 uncertain parameters remain, respectively, for the baseline and alternative RAP content scenarios. Emissions are regarded as background processes, and hence are not included in the uncertainty analysis. Moreover, the additional uncertainty related to intermediate flows was not included since there are no concerns about the use of proxy process profiles.

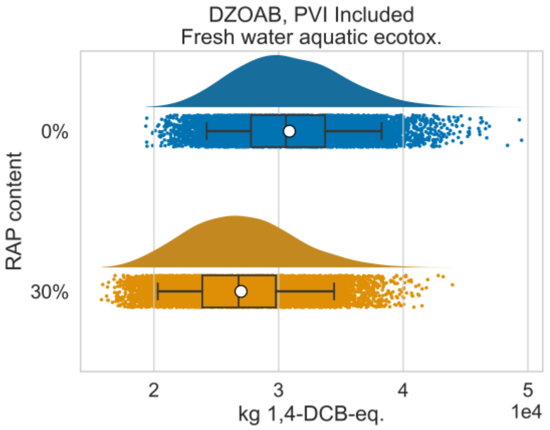
A total of 12,000 LHS simulations for each scenario were performed using the SALib python library (Herman & Usher, 2017) to obtain the stochastic environmental impacts of QAN0331. The environmental impacts of each simulation were calculated using OpenLCA with a Python interface based on the workflow developed by Jaxa-Rozen et al., (2021a). The LCIA results for the different scenarios and CML impact categories are illustrated in Figure 34 and Figure 35. The results reveal that scenarios that include RAP generally present lower environmental impacts, although this effect is almost imperceptible when the use phase is considered. This is due to the overwhelming contribution of the environmental impacts associated with PVI, which outweigh the influence of the remaining phases. The tabular results and MKI values of the case study can be found in Appendix G.

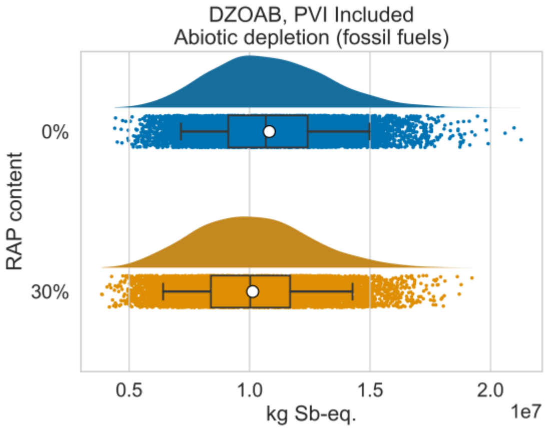
Table 52. Parameter uncertainty breakdown.

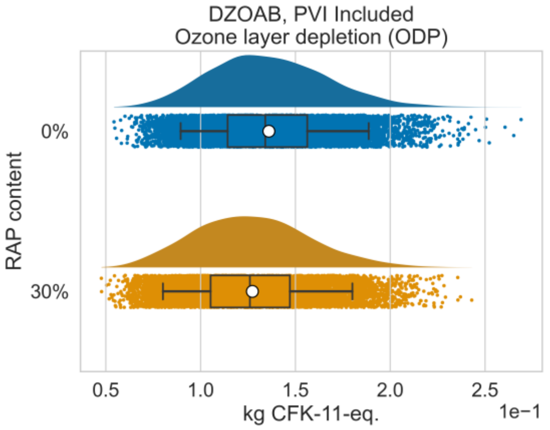
				Data quality scores					Uncertainty				Deterministic value (dv)		PDF parameters				
Mod.	Input parameter	Unit	Tag	1	2	3	4	5	Additional (lognormal σ)	Basic	Total (TPU)	Source	0%	30%	Type	Mean	Std	Lower bound	Upper bound
A1	Raw materials content																		
	Bitumen	kg	A1_bitumen	2	1	1	1	1	0.0006	0.0006	0.0012	ecoinvent	52.00	41.20	lognormal	ln(dv)	sqrt(TPU)	▨	▨
	Crushed sand	kg	A1_crushedsand	2	1	1	1	1	0.0006	0.0006	0.0012	ecoinvent	43.00	34.20	lognormal	ln(dv)	sqrt(TPU)	▨	▨
	Crushed stone 3	kg	A1_crushedstone3	2	1	1	1	1	0.0006	0.0006	0.0012	ecoinvent	852.00	586.10	lognormal	ln(dv)	sqrt(TPU)	▨	▨
	Asphalt granulate	kg	A1_asphaltgranulate	2	1	1	1	1	0.0006	0.0006	0.0012	ecoinvent	0.00	300.00	lognormal	ln(dv)	sqrt(TPU)	▨	▨
	Own material	kg	A1_ownmaterial	2	1	1	1	1	0.0006	0.0006	0.0012	ecoinvent	0.00	9.40	lognormal	ln(dv)	sqrt(TPU)	▨	▨
	Medium filler	kg	A1_mediumfiller	2	1	1	1	1	0.0006	0.0006	0.0012	ecoinvent	51.00	27.00	lognormal	ln(dv)	sqrt(TPU)	▨	▨
	Drip resistant material	kg	A1_dripresistantmaterial	2	1	1	1	1	0.0006	0.0006	0.0012	ecoinvent	2.00	2.10	lognormal	ln(dv)	sqrt(TPU)	▨	▨
A2	Transport distance to plant																		
	Bitumen - truck	km	A2_bitumen	2	2	1	2	1	0.000725	0.12	0.1207	ecoinvent	250.00	250.00	lognormal	ln(dv)	sqrt(TPU)	▨	▨
	Crushed sand - truck	km	A2_crushedsand_t	2	2	1	2	1	0.000725	0.12	0.1207	ecoinvent	25.00	25.00	lognormal	ln(dv)	sqrt(TPU)	▨	▨
	Crushed sand - inland vessel	km	A2_crushedsand_iv	2	2	1	2	1	0.000725	0.12	0.1207	ecoinvent	660.00	660.00	lognormal	ln(dv)	sqrt(TPU)	▨	▨
	Crushed stone 3 - truck	km	A2_crushedstone3_t	2	2	1	2	1	0.000725	0.12	0.1207	ecoinvent	25.00	25.00	lognormal	ln(dv)	sqrt(TPU)	▨	▨
	Crushed stone 3 - inland vessel	km	A2_crushedstone3_iv	2	2	1	2	1	0.000725	0.12	0.1207	ecoinvent	53.00	53.00	lognormal	ln(dv)	sqrt(TPU)	▨	▨
	Crushed stone 3 - sea vessel	km	A2_crushedstone3_sv	2	2	1	2	1	0.000725	0.12	0.1207	ecoinvent	933.00	933.00	lognormal	ln(dv)	sqrt(TPU)	▨	▨
	Own material - truck	km	A2_ownmaterial_t	2	2	1	2	1	0.000725	0.12	0.1207	ecoinvent	0.00	25.00	lognormal	ln(dv)	sqrt(TPU)	▨	▨
	Own material - inland vessel	km	A2_ownmaterial_iv	2	2	1	2	1	0.000725	0.12	0.1207	ecoinvent	0.00	150.00	lognormal	ln(dv)	sqrt(TPU)	▨	▨
	Medium filler - truck	km	A2_mediumfiller	2	2	1	2	1	0.000725	0.12	0.1207	ecoinvent	136.00	136.00	lognormal	ln(dv)	sqrt(TPU)	▨	▨
	Drip resistant material - truck	km	A2_dripresistantmaterial	2	2	1	2	1	0.000725	0.12	0.1207	ecoinvent	177.00	177.00	lognormal	ln(dv)	sqrt(TPU)	▨	▨
A3	Energy consumption																		
	Natural gas	m3	A3_naturalgas	2	1	1	1	1	0.0006	0.0006	0.0012	ecoinvent	7.43	8	lognormal	ln(dv)	sqrt(TPU)	▨	▨
	Electricity	kWh	A3_electricity	2	1	1	1	1	0.0006	0.0006	0.0012	ecoinvent	6.23	5.61	lognormal	ln(dv)	sqrt(TPU)	▨	▨
	Diesel	l	A3_diesel	2	1	1	1	1	0.0006	0.0006	0.0012	ecoinvent	0.12	0.12	lognormal	ln(dv)	sqrt(TPU)	▨	▨
A4	Transport distance to construction site																		
	Distance to construction site	km	A4_distance	2	2	1	2	1	0.000725	0.12	0.1207	ecoinvent	44.40	44.4	lognormal	ln(dv)	sqrt(TPU)	▨	▨
A5	Energy consumption																		
	Asphalt set (spreader + roller)	l	A5_construction_1000	2	1	2	1	1	0.0008	0.0006	0.0014	ecoinvent	0.32	0.32	lognormal	ln(dv)	sqrt(TPU)	▨	▨
B1-PVI	Extra fuel consumption																		
	Cars	l	B_cars_avg	2	3	1	1	1	0.0012	46675.05	46736.19	This study	68967.84	68967.84	normal	dv	TPU	5836.96	274818.2
	HDV	l	B_HDV_avg	2	3	1	1	1	0.0012	10516.89	10534.82	This study	17729.00	17729	normal	dv	TPU	2085.91	76561.65
	HDV + trailer	l	B_HDVtrailer_avg	2	3	1	1	1	0.0012	41941.30	41990.32	This study	58536.78	58536.78	normal	dv	TPU	3960.95	252107.1
C1	Energy consumption																		
	Milling + cleaning + sweeping	l	C1_removal_1000	2	1	2	1	1	0.0008	0.0006	0.0014	ecoinvent	0.77	0.77	lognormal	ln(dv)	sqrt(TPU)	▨	▨
C2	Transport distance to processing																		
	Distance to processing	km	C2_distance	2	2	1	2	1	0.000725	0.12	0.1207	ecoinvent	44.40	44.4	lognormal	ln(dv)	sqrt(TPU)	▨	▨
C3	Diesel consumption																		
	Crane and shovel	l	C3_craneandshovel	2	1	2	1	1	0.0008	0.0006	0.0014	ecoinvent	0.19	0.185	lognormal	ln(dv)	sqrt(TPU)	▨	▨
	Breaker	l	C3_breaker	2	1	2	1	1	0.0008	0.0006	0.0014	ecoinvent	0.19	0.185	lognormal	ln(dv)	sqrt(TPU)	▨	▨

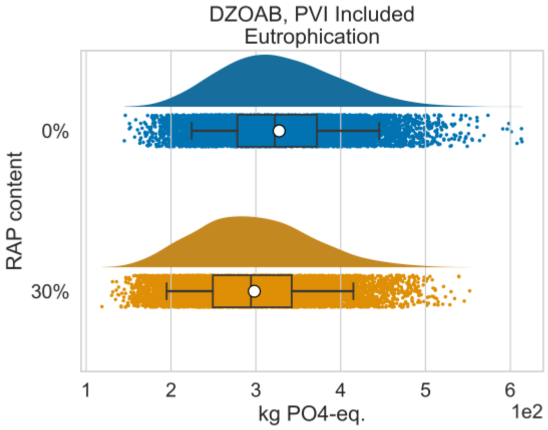

DZOAB, PVI Included
Human toxicity

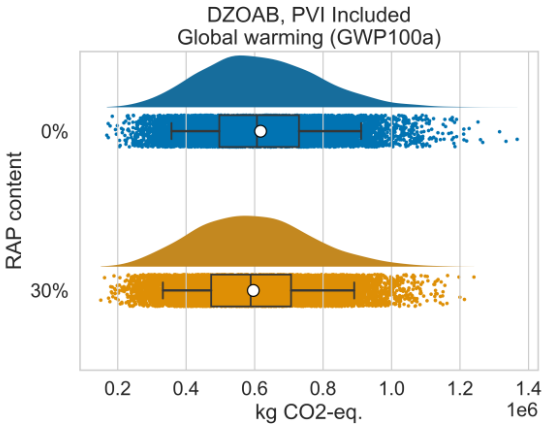

DZOAB, PVI Included
Abiotic depletion

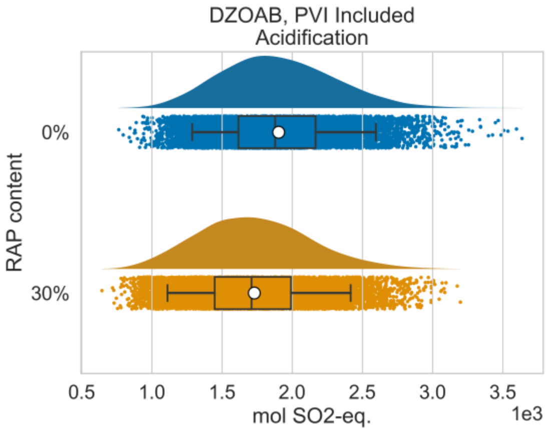

DZOAB, PVI Included
Fresh water aquatic ecotox.


DZOAB, PVI Included
Abiotic depletion (fossil fuels)


DZOAB, PVI Included
Ozone layer depletion (ODP)


DZOAB, PVI Included
Eutrophication


DZOAB, PVI Included
Global warming (GWP100a)


DZOAB, PVI Included
Acidification

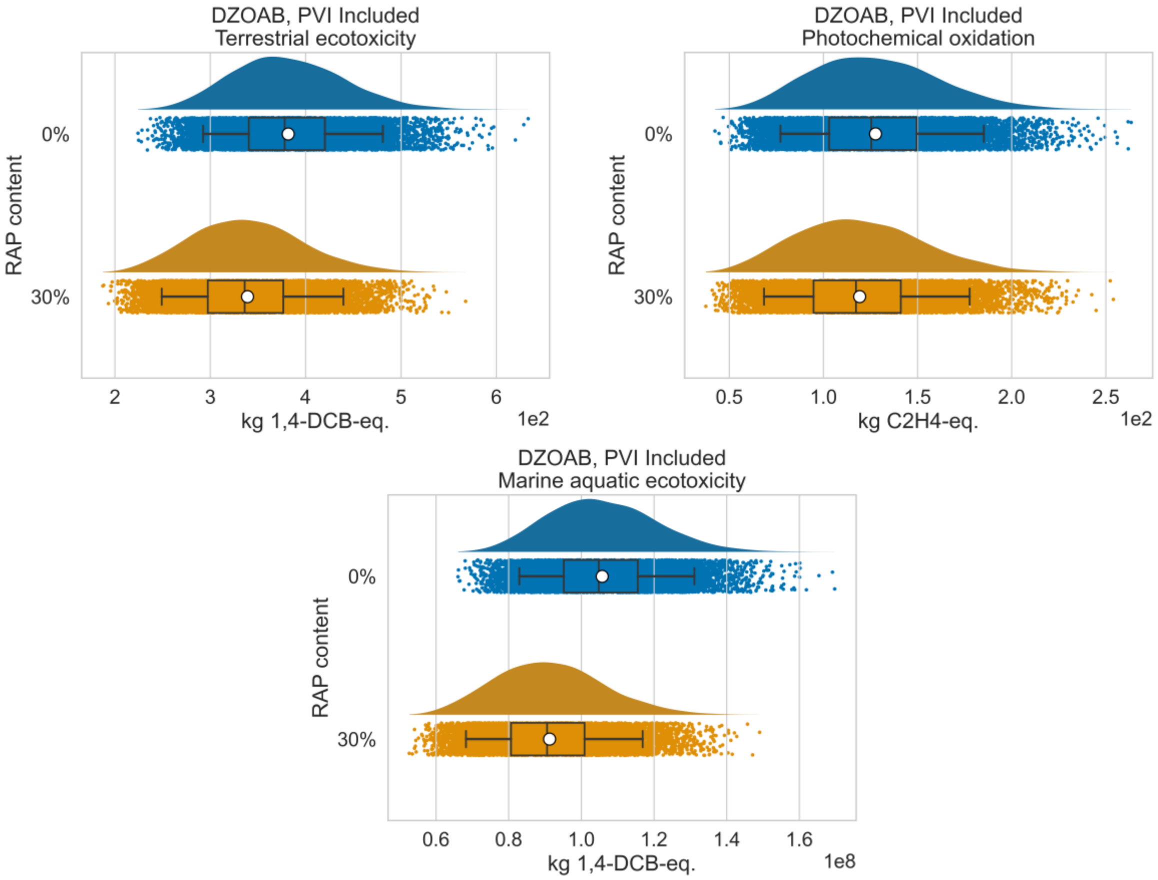
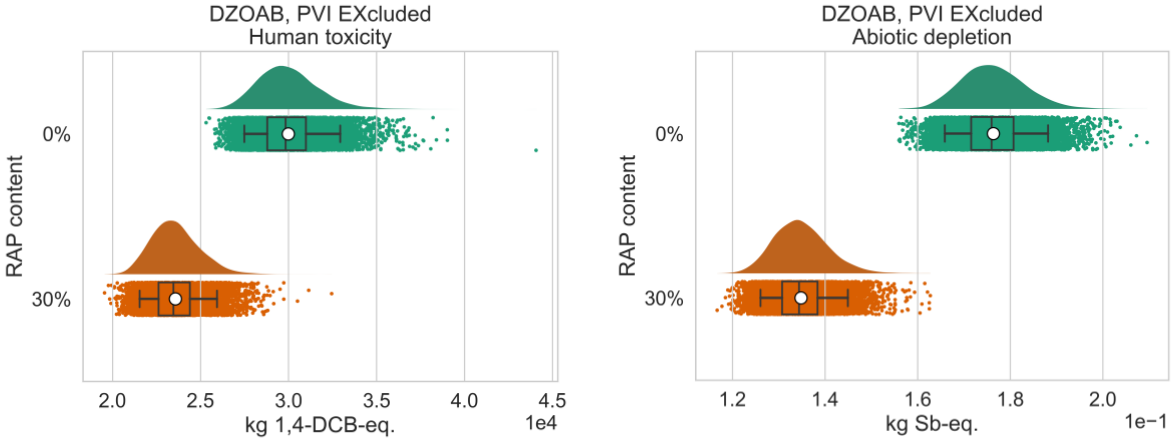
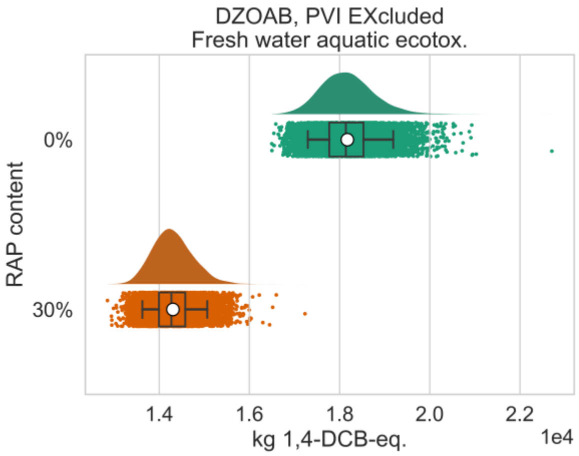
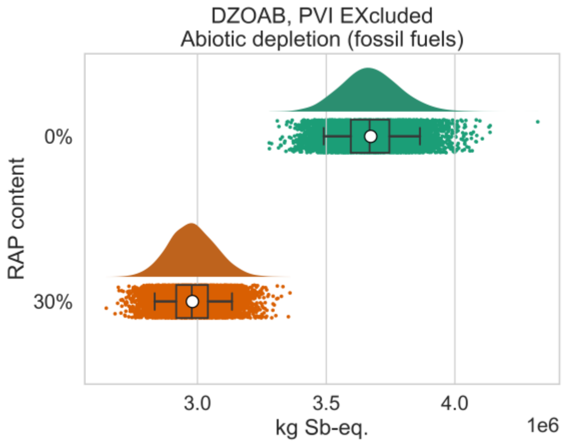
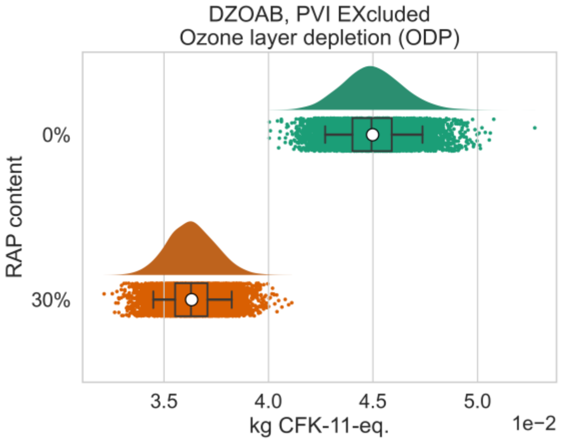


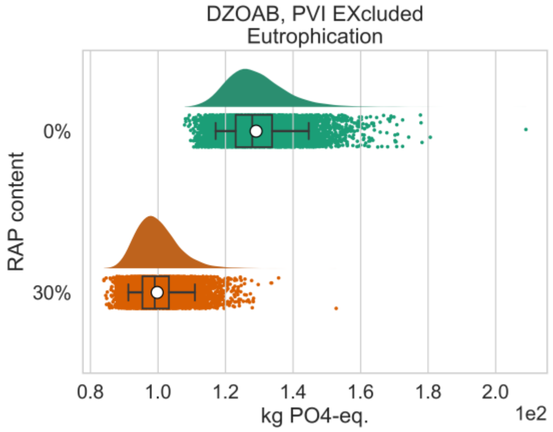
Figure 34. Stochastic environmental impacts for QAN0331: DZOAB overlay, baseline and alternative RAP content, PVI included. Results for 12,000 LHS simulations.

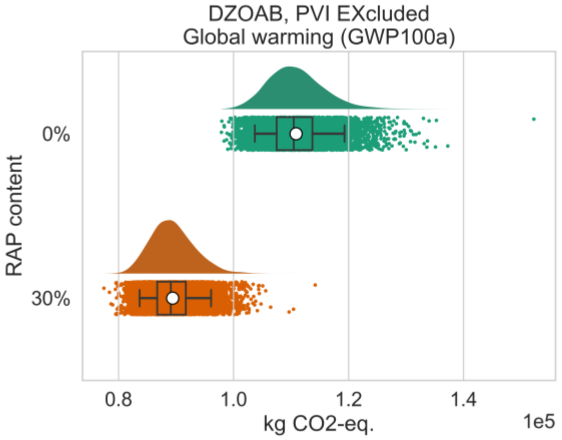


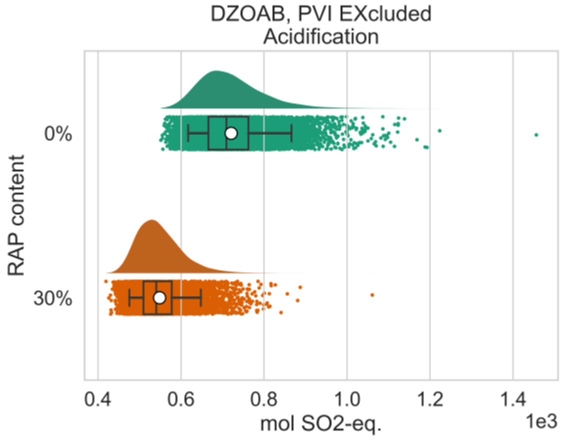

DZOAB, PVI EXcluded
Fresh water aquatic ecotox.
RAP content
0%
30%
1.4
1.6
1.8
2.0
2.2
kg 1,4-DCB-eq.
1e4

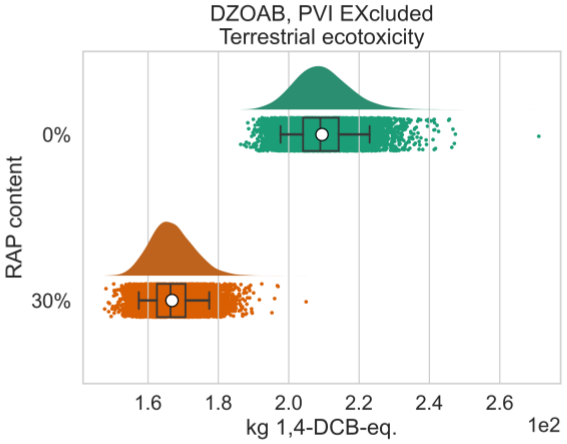

DZOAB, PVI EXcluded
Abiotic depletion (fossil fuels)
RAP content
0%
30%
3.0
3.5
4.0
kg Sb-eq.
1e6

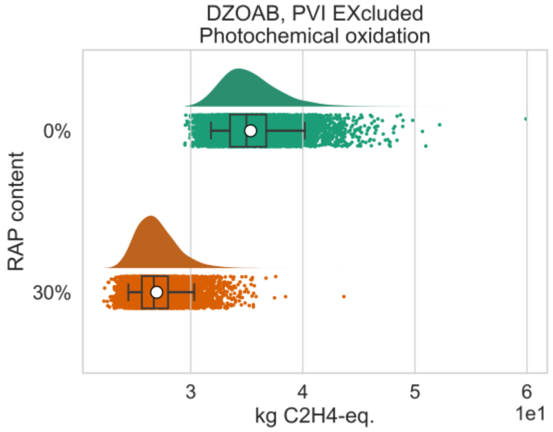

DZOAB, PVI EXcluded
Ozone layer depletion (ODP)
RAP content
0%
30%
3.5
4.0
4.5
5.0
kg CFK-11-eq.
1e−2


DZOAB, PVI EXcluded
Eutrophication
RAP content
0%
30%
0.8
1.0
1.2
1.4
1.6
1.8
2.0
kg PO4-eq.
1e2


DZOAB, PVI EXcluded
Global warming (GWP100a)
RAP content
0%
30%
0.8
1.0
1.2
1.4
kg CO2-eq.
1e5


DZOAB, PVI EXcluded
Acidification
RAP content
0%
30%
0.4
0.6
0.8
1.0
1.2
1.4
mol SO2-eq.
1e3


DZOAB, PVI EXcluded
Terrestrial ecotoxicity
RAP content
0%
30%
1.6
1.8
2.0
2.2
2.4
2.6
kg 1,4-DCB-eq.
1e2


DZOAB, PVI EXcluded
Photochemical oxidation
RAP content
0%
30%
3
4
5
6
kg C2H4-eq.
1e1

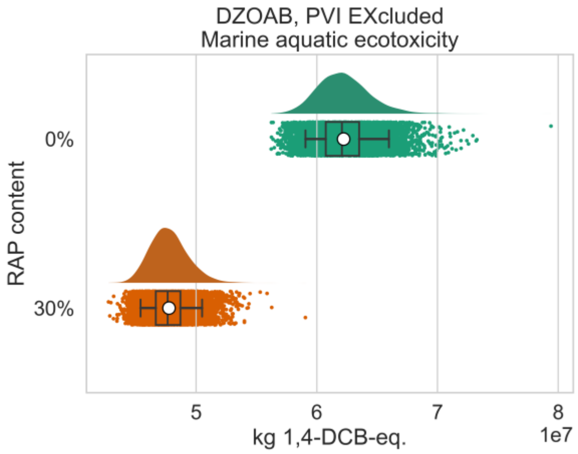


Figure 35. Stochastic environmental impacts for QAN0331: DZOAB overlay, baseline and alternative RAP content, PVI excluded. Results for 12,000 LHS simulations.

The sensitivity analysis was performed on scenarios that did not account for PVI. Initial sensitivity results showed that the impact of PVI on the uncertainty of the environmental impacts was so significant that it overshadowed the influence of other input parameters. In scenarios that include PVI, additional fuel consumption has the greatest influence on the uncertainty of the outcomes. This can be attributed to the large variability and predominant contribution of extra fuel consumption to the environmental impacts. In contrast, the contribution of other parameters in the scenarios thereof is relatively similar and mostly below the order of 1%. To overcome this limitation and obtain more reliable estimates of the sensitivity of the results to other input variations, scenarios that excluded PVI were analyzed.

To perform a first-order Sobol-based GSA, a total of N = n(k+2) samples were generated for each RAP scenario, where n is the number of simulations (2,500) and k is the number of input parameters (22 or 26 depending on the RAP scenario). Specifically, 60,000 Sobol samples were generated for the baseline scenario, and 70,000 for the alternative scenario. Each sample was then analyzed using the same strategy followed to generate and conduct the LHS simulations. The input-output pairs from both LHS and Sobol sampling were employed to conduct the GSA study using Extra Trees, PAWN, and Sobol methods. First-order and total Sobol indices were calculated using the SALib python library (Herman & Usher, 2017). The Extra Trees MDI measure was estimated applying an Extra Trees regression using the scikit-learn Python library (Pedregosa et al., 2012). Finally, the K-max and K-median PAWN values were computed using the PAWN implementation of the SAFE toolbox Python library (Pianosi et al., 2015). The performance of the GSA was aided by the publicly available GSA python workflow developed by Jaxa-Rozen et al., (2021a).

Figure 36 shows the results of the sensitivity analysis for the impact categories of global warming and abiotic depletion. The results indicate that the outcomes from all three GSA methods are comparable. Notably, transport has a significant effect on uncertainty, particularly the transportation of large aggregates via trucks and transoceanic ships in module A1, and freight transport to and from the construction site in modules A4 and C2. This can likely be credited to the large uncertainty values assigned to transport exchanges by the ecoinvent method.

Taking a closer look at other life cycle processes, bitumen and large size aggregated in A1 and A2 processes, as well as the consumption of natural gas for mixture heating in module A3, are the major contributors to uncertainty after transport. In the alternative RAP scenario, asphalt granulate is partially used in place of large size aggregate, reducing the impact of large size aggregate on the uncertainty of the abiotic depletion results in both A1 and A2. This suggests that uncertainty is also associated with a process's contribution to the total impact, although this is not the case for the same processes in the global warming impacts.

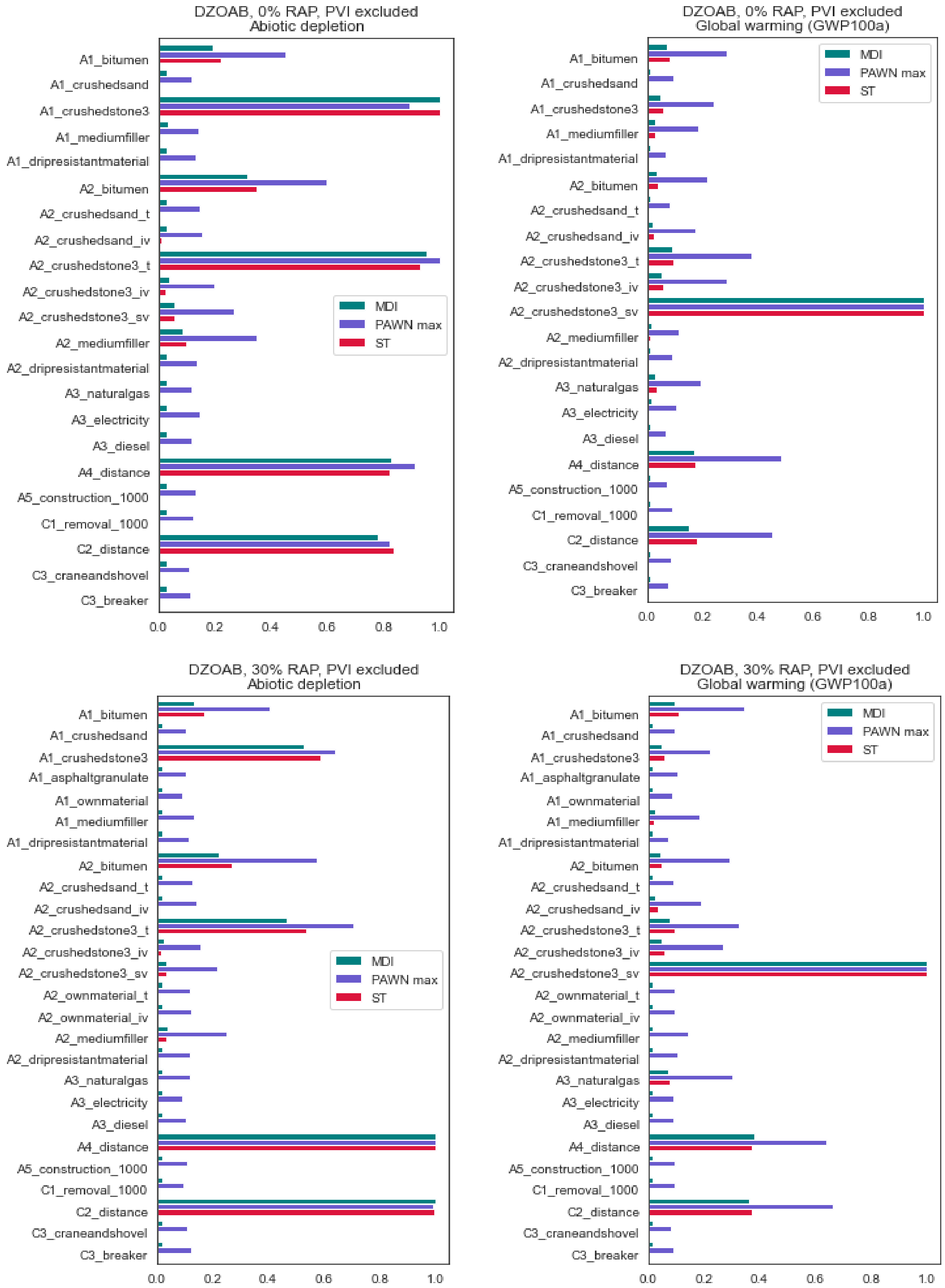


Figure 36. GSA results.

For a more detailed discussion and comparison of all the case study results obtained from the sensitivity analysis, both for scenarios that include and exclude PVI, readers are referred to Appendix H, where the GSA methods performance and outcomes are further discussed and compared.

6.1.1 CASE STUDY CONCLUSION

The case study presented in this project applied the EPMF to evaluate the environmental performance of a functional overlay rehabilitation measure. The results demonstrated the importance of including PVI in the analysis, as the reduction of impacts occurring in other phases becomes imperceptible when the use phase is considered. This highlights the significance of ensuring that the pavement remain in good condition during the analysis period to reduce extra fuel consumption due to increased RR.

The sensitivity analyses conducted in this study revealed that the contribution of PVI to the uncertainty in the results was overwhelming, indicating the need for further exploration of the influence of other parameters on the uncertainty. By conducting sensitivity analyses using scenarios that excluded PVI, the study showed that transportation processes have a significant impact on the uncertainty of the outcomes. This suggests that transportation processes have the biggest potential for reductions, and that refining transport data can reduce the uncertainty of the outcomes and improve their reliability. However, the uncertainty imposed by PVI should not be dismissed outright, and more reliable PVI models should be developed to improve the quality of the analysis and reduce the uncertainty on the results.

Overall, the EPMF can advance the applicability of LCA in the context of pavement M&R and improve the understanding of the effects of uncertainties on the outcomes. The use of the EPMF facilitated the identification of areas with the highest potential for environmental performance improvements by determining the extent to which impacts can be reduced. However, it should be noted that the uncertainty analysis is computationally expensive, particularly when exploring different scenarios and when employing Sobol-based GSA. Extra Trees and PAWN proved to be more efficient techniques that deliver results comparable to Sobol, reiterating the results obtained in previous studies (Jaxa-Rozen et al., 2021b; Jaxa-Rozen & Kwakkel, 2018). Furthermore, the stochastic impact results cannot be easily disaggregated into phases using the digital tools employed. Further research could explore alternative methods to make the results more accessible, potentially by developing additional tools or software that can more easily disaggregate the results. Nonetheless, the outcomes of this study provide valuable insights into the environmental performance of pavement M&R strategies and offer a solid foundation for future research in this area.

6.2 INTERVIEWS

Interviews with representatives of the Dutch asphalt industry and the PPO branch of the RWS were conducted to retrieve information regarding the tenders of road pavement M&R projects, the role that LCA plays therein, and their general views on the subject.

The interviews had an average duration of one hour. Company representatives were contacted via the ASPARi network[29], whereas the RWS interviewees were reached internally. Table 53 holds information regarding the interviewees, their organization, and when were they interviewed. The interviews were set up in an unstructured format to gain in-depth insights into the experiences and perspectives of the participants and allow them to guide the discussion. The tendering process stage of PM is a complex and multifaceted area of research. Unstructured interviews provide the opportunity to gain a deeper understanding on how the participants perceive the current use of LCA in PM, its strengths and weaknesses, and how it fits into the broader context of their work. The goal of the interviews was to identify key themes and issues that may not have been initially apparent to guide and validate the design tasks and put together the further implementation plan of the MF.

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[29] ASPARi is a collaborative network of organizations in the asphalt road construction sector that represents over 80% of the sector. The organization was established in response to changing requirements and challenges in the sector over the years. See www.aspari.nl for more information.

Table 53. Schedule of the interviews.

Representative	Company	Date
Steven Mookhoek	Dura Vermeer	24-05-2022
Marleen Versteegen	Dura Vermeer	24-05-2022
Ronald Diele	ReintenInfra BV	25-05-2022
Marco Oosterveld	BAM	02-06-2022
Berwich Sluer	Boskalis	09-06-2022
Tessa Bouzidi	BAM	15-06-2022
Jorgen de Wijs	AsfaltNu	27-06-2022
Elizabeth Keijzer	TNO	10-11-2022
Monique Dorresteijn	RWS – PPO	09-12-2022
Zoran Steinmann	RWS – PPO	19-01-2023

The results of the interview highlighted the importance of including uncertainty analysis into the evaluation of environmental performance using LCA and brough to light several issues regarding the current focus of environmental performance and LCA in PM. Table 54 summarizes the results of the interviews.

Table 54. Design considerations product of the interviews.

Theme	Description
Perceived uncertainties	Reliability in the prediction of the service life of a new asphalt layer.
	Predictions about the construction / removal works in the distant future are based on many assumptions and fraught with uncertainty.
	The definition of the MKI weighting values is perceived as highly uncertain.
	Module D is perceived as a circularity indicator that captures the value of recycling asphalt materials in the future. However, module D implies benefits outside the system boundaries that (1) are not necessarily true, and (2) are double accounted as RAP or asphalt granulate enters to the system free of burden.
RAP	Typically, reductions in MKI values are addressed in modules A1 through A3. For instance, the importation of raw materials has significant environmental effects. Consequently, the use of secondary materials has become is prevalent in the asphalt domain. High RAP content mixtures do exist, but their implementation is constrained by RAP availability. Lower MKI coincides to higher RAP levels, but this restriction impedes the reduction. As lower MKI values usually require the use of secondary materials, sourcing RAP from other clients may be necessary.
Environmental performance in PM	The RWS is thought to have little active involvement in improving environmental performance. RWS outlines the functional specifications that must be met by the bidders to encourage innovation and prevent monopolization. Environmental requirements, however, are not clearly stated. Instead, contractors are required to deliver the environmental performance of their bids, which must fall within an MKI value range provided by the RWS. This strategi is the way in which the RWS addresses environmental performance, which in turn, shifts all the responsibility in mitigating the environmental impacts of pavements to the contractors. Beyond accountability, there are concerns surrounding the underlying principles guiding the definition of the MKI range to which the contractors must adhere. These ranges are underpinned by arbitrary decisions and multiple assumption. For instance, the approach involves increasing MKI values derived from DuboCalc and based on unverified data (NMD category 3 data) by 30%. The extent to which contractors invest efforts to attain lower MKI values depends on the difficulty of reaching the lower bound specified in the ranges. Notably, achieving lower MKI values can lead to a more significant reduction in the overall cost of bid proposals. However,

Theme	Description
	contractors emphasize that a singular focus on MKI values may not be sufficient to ensure robust environmental performance.
	In order to ensure compliance with the MKI values agreed upon during the tender process, the RWS monitor environmental performance throughout later stages to identify any changes or deviations from the proposal. For example, they rigorously check that the distances and mixtures' composition proposed by contractors are indeed accurate. In recent years, fines have been implemented for failure to meet proposed MKI values, marking a significant shift from a previous lenient approach where non-compliance often went unchecked.
	The procurement team frequently experiences uncertainty concerning the MKI values submitted by contractors. They are aware that there is a possibility of influencing results towards optimistic figures, and they lack a systematic method to determine the credibility of the presented numbers. The presence of uncertainty within the MKI values raises significant challenges in evaluating their reliability. While it's feasible to track whether parameter definitions align with the proposed during monitoring, a distinct and more intricate task involves validating that the attributed impacts to these parameters truly correspond to their stated effects.
	DuboCalc was designed specifically for large construction projects and is often perceived as a black box model. At this point, the RWS is no longer constructing as many new projects as in the past, and DuboCalc must adapt to meet the RWS's evolving needs, which is hindered by the lack of understanding of the software.
Inconsistency	The specifications of the LCA studies required for the tenders are highly variable. For example, the analysis period of the tenders is always different; they typically span from 50 to 100 years. The RWS does this to incentivize contractors to think about asphalt durability and circularity.

There are many perceived uncertainties in the current way in which M&R is assessed: the predicted lifespan of the asphalt mixtures, the assumptions made for future scenarios, the definition of the MKI weighting factors themselves, and the handling of Module D. Additionally, the availability of RAP was revealed to be a big issue in the sector. Asphalt providers have been able to design asphalt mixtures that can handle large contents of RAP. However, chances are that the RAP quantities required to produce such mixtures won't be available at the time when they are needed, introducing uncertainty regarding the RAP contents of the mixtures. Given that environmental gains are mainly targeted in modules A1-A3, this issue is of particular significance.

These outcomes carry significant implications for design, particularly influencing the identification of scenario uncertainties and the specification of the analysis period down to individual M&R cycles. Notably, the uncertainty surrounding MKI weighting values remains unaddressed in the EPMF due to constraints related to scope and time.

The interviews also exposed that the way in which RWS incorporates environmental performance is perceived as lacking and inarticulate. Contractors are not sure on how the RWS define the environmental performance ranges that they must meet. Furthermore, the perceived the participation of the RWS in improving environmental performance as rather superficial, given that nearly all the tasks to improve environmental performance are allocated to the industry sector only.

The RWS also acknowledges certain shortcomings within the existing approach to environmental performance in procurement. Specifically, PPO raises concerns regarding the accuracy and reliability of the environmental performance data submitted by the contractors. There is apprehension that the MKI figures presented in bids might be unrealistic, filled with uncertainty, and heavily influenced by the choices made by the practitioners. While mechanisms exist to verify the consistency between proposed and executed activities, the challenge lies in the absence of systematic approaches to ascertain the coherence of the MKI values provided by the contractors during procurement. This situation underscores the complexities inherent in the current approach to addressing environmental performance, prompting a need for more robust and nuanced strategies.

Chapter 8 delves more deeply into the topics of environmental performance in PM, focusing on the benefits of implementing the EPMF, and how this can address some of the issues identified in the interviews. In general, the EPMF is perceived as an instrument that could address some of the issues revealed in the interviews, and offer several key benefits to the current PM process beyond ICO's action field:

1. **Proactive environmental mitigation:** The EPMF empowers the RWS to play a more proactive role in mitigating environmental impacts. The EPMF can be leveraged in early PM to seek environmental improvement early in the process. A more equitable distribution of environmental responsibilities can contribute to enhancing contractors' perception of the role played by the RWS.

2. **Sound environmental performance ranges:** The framework facilitates the establishment of robust and well-grounded environmental impact ranges. The uncertainty ranges obtained with the EPMF can subsequently be utilized to delineate the MKI range that contractors are required to adhere to throughout the procurement process. This approach ensures that the foundation of these ranges is solid and results in values that are more representative.

3. **Coherence check:** The EPMF provides the RWS with ranges of uncertainty for input parameters and environmental impacts. This equips the RWS to examine the likelihood of the input and output values presented by the contractors in their environmental performance proposals. Such an approach enables the RWS to evaluate the logical coherence of the proposals and identify potential inconsistencies in the provided figures. As this approach aids in evaluating the credibility of the MKI value put forth by the contractors, it enhances the overall quality of decision-making at procurement.

4. **Contractor safeguards:** The environmental performance figures submitted by the contractors are also the subject of uncertainty. Incorporating uncertainty factors in the PM process would allow contractors to be bounded by an MKI range instead of a singular MKI value during execution. By providing a permissible margin of error between estimated and achieved values, the framework safeguards them against potential penalties arising from inflexible benchmarks.

6.3 FOCUS GROUP

A workshop style focus group was conducted in the offices of the RWS in Utrecht on the 24th of November of 2022. I, the EngD candidate, served the role of the workshop moderator. Members of GPO, namely ICO members, and roads and geotechnical engineering (W&G) experts, as well as the UT supervisors of the EngD project, were present in the focus group (Table 55). The themes of the EPMF design functionality and implementation in its context of use govern the workshop. The session was structured in four parts:

1. **Introduction:** The session launched with an introduction to the EPMF design, its context of use, and the kind of outcomes that it produces.

2. **Design review:** Participants were later divided into three small groups and given the task of discussing the design of the EPMF in terms of completeness, reliability, transparency/clarity, and flexibility. Furthermore, they were given open-ended questions to explore their opinions on (1) whether the design of the EPMF achieve what was originally intended with the EngD project, (2) the strengths and weaknesses of the design, and (3) the biggest areas of opportunity for adjustments and improvements. The groups were thereafter asked to present their views to the larger group and engage into a plenary discussion guided by the moderator.

3. **Implementation review:** The participants were split into the previously assigned groups to discuss the implementation of the MF. Open-ended questions sought to retrieve the views of the participants on outlined implementation sub-themes, namely (1) how do the envision that the EPMF would work and be implemented in the RWS context, (2) what may hinder or promote implementation, (3) what needs to be change or improve for a better implementation, (4) who will oversee the operation and maintenance of the MF, (5) how do they think that the EPMF relates to the current RWS practice, knowledge and tools, and (6) what follow up projects do they consider worthy to purse based on the MF. Furthermore, participants were asked to discuss the EPMF based on its relevance, compatibility, and integration and complementarity (implementation potential). Afterwards, the groups were again asked to present their views to the larger group and engage into a plenary discussion guided by the moderator.

4. **Final review:** The results of the workshop were grouped and presented to the large group. The insights obtained were presented, and final remarks were discussed. This step serves the purpose of wrapping up the session and giving space to the participant to add additional discussion points if necessary.

Table 55. Focus group participants.

Participants	Organization / department
João Oliveira dos Santos	University of Twente
Andreas Hartmann	University of Twente
Fiola van der Pijl	RWS – ICO
Rob Treiture	RWS – ICO
Leon Schouten	RWS – ICO
Dennis van Leeuwen	RWS – ICO
Alexander Schippers	RWS – ICO
Jos Lucas	RWS – W&G
Rob Hofman	RWS – W&G

Table 56. Focus group workshop results.

Theme	Sub-theme / requirement	Description
Design	Does the design of the EPMF achieves what the EngD project intended?	The participants agreed that the EPMF fulfills the project's intended goals from the time it was commissioned.
	Strengths of the design	It is a strength of the design that it is modular and adaptable to change.
	Areas of opportunity for design adjustments and improvements.	Expand the maintenance treatments catalogue.
	Applicability	The range of included maintenance treatments is limited. Treatments such as rejuvenators are not considered. In addition, the question arose as to whether the defined M&R product cases encompass all possibilities.
	Completeness	Participants acknowledged the completeness of the LCA framework as M&R was appropriately approached and its life cycle was accurately represented and evaluated.
	Representativeness	This requirement was met as the EPMF is based on consistent and up-to-date sector information (such as the NL-PCR and official LCA guidelines).
	Reliability	As a result of the estimation and communication of uncertainty regarding the results, the perceived reliability is high.
	Transparency/clarity	Some participants believed that certain knowledge backgrounds were essential for understanding the underlying principles behind the EPMF's design decisions, which not everyone possessed. They stress the importance of presenting a clear and

Theme	Sub-theme / requirement	Description
		precise, understandable explanation of its structure and operation to make it usable.
	Flexibility	The framework's modular approach increases the EPMF's perceived flexibility. The EPMF should allow for changes and modifications in response to new information, as well as clearly state how to do so.
Implementation	Implementation vision in the RWS context	The EPMF currently serves the purpose of raising environmental awareness. It is a source of information.
	Enablers and barriers	The fragmentation of the PM process is an impediment to implementation. For example, due to budgetary constraints, the district may be unable to follow ICO's advice, which has an impact on the estimated environmental performance. A disconnection between asset managers and project managers could make environmental performance calculations ineffective.
	Changes and improvements for a better implementation	It would be beneficial to add the EPMF to IVON2. ICO would like to see an additional column with environmental impacts added to IVON2.
	Overview of the maintenance and operation of the framework	They recognize the importance of appointing someone to manage the EPMF. However, in order to properly manage the EPMF, they must fully comprehend and account for its needs.
	Relation to the current RWS practice, knowledge, and tools	There is no direct link to other projects currently being developed in the RWS. The EPMF should be included in the OBR for distribution to other RWS branches involved in the PM process.
	Follow-up projects	During the workshop, no specific plans for follow-up projects were developed. However, there is interest, and they may consider expanding the EPMF research or similar, related projects.
	Relevance	The EPMF is relevant to its context because it represents a pathway towards sustainable PM. Furthermore, it raises awareness about the environmental impacts of PM strategies. Its implementation would benefit not only ICO, but also the rest of the PM actors, notably the regional branches of the RWS, which rarely consider environmental criteria in their decision-making.
	Compatibility	Since DuboCalc does not offer an adequate platform for what the EPMF intends, there is no direct connection between the EPMF and DuboCalc. However, Python and OpenLCA, both open access tools, are suitable application platforms for the EPMF as demonstrated with the digital tool. DuboCalc's inability to implement the EPMF, which is tailored to the need of the early PM stages where ICO operates, allows ICO to justify the use of tools other than DuboCalc. However, the EPMF currently involves the use of the privately-owned and fee-based ecoinvent database. The RWS would certainly find the NMD more applicable to its context, and perhaps easier to access. However, to employ the NMD, the EPMF digital tool must be adapted to SimaPro, the only LCA tool other than DuboCalc that supports the NMD, which is not open source and perhaps may not offer the capabilities that are necessary for the EPMF to deliver its intended results.
	Implementation potential (integration and complementarity)	The EPMF has the potential to be implemented by ICO members and complement their work. It does not change the way in which they generate the MJPV, but rather adds to it. There is not an immediate challenge to its integration in ICO. The main implementation issue rather concerns to the larger PM cycle and originates in the institutional fragmentation experienced within the RWS. Better communication between the actors involved in the different stages of PM is needed to ensure that the EPMF works as intended and that its results are not lost in the later stages of the PM cycle. Ideally, the results produced by the EPMF should be of interest for all the actors involved in the PM cycle, and its use should be eventually extended to the rest of the stages.

In general, the EPMF was perceived as a good starting point to bridge cost and environmental performance in the decision-making of PM. Participants were satisfied with its design and functionality. They approved of the outcomes that the EPMF produces and saw a clear link between the project and the sustainability agenda that the RWS pursues. The discussion provided important insights, especially regarding implementation, which are further considered in the implementation plan found in Chapter 7.4.5. In principle, the most obvious recommendation resulting from this workshop would be to upgrade DuboCalc to adopt the methodology of the EPMF. However, that comes with many challenges and may not be feasible at this time. Then, it may be beneficial to upgrade to more sophisticated LCA software, such as Brightway2 (Mutel, 2017), an open-source Python LCA platform helpful for models that extend beyond the traditional boundaries of LCA.

Design feedback was less prominent, as participants were generally satisfied with the way in which the EPMF is designed. The main design observation is that the maintenance treatments that it considers are rather limited. The range of maintenance treatments was defined based on the official resources of the RWS (GPO, 2022). Treatments other than the ones outlined by the RWS were outside the design scope. However, the flexibility of the LCA framework allows for their further future integration. This realization encouraged the further revision of the rehabilitation cases, which only contained four different product cases initially. Following the focus group, additional cases were developed to capture the variations in the system boundaries when composite mixtures, namely ZOABTW and ZOABTF, are present.

Lastly, the participants agreed that an informative final session after the project has concluded would be beneficial to consolidate the use of the EPMF in the ICO department and discuss potential follow up projects. The full results of the workshop and its implications for the design and implementation are presented in Table 56.

6.4 PERFORMANCE AND REQUIREMENTS VERIFICATION

This section presents an evaluation of the accuracy in the performance of the EPMF, as well as a verification of the requirements, aiming to summarize how each design requirement is accounted for in the EPMF and its subcomponents.

To evaluate the accuracy of the EPMF's performance, benchmark LCA results that could be compared to the LCIA results generated by the framework were gathered. The most recent LCA background report of the branch reference mixtures provided deterministic results of DZOAB mixtures with 0% and 30% RAP (Bak et al., 2022). These results were compared to the deterministic results of case study QAN0331. Appendix I includes the deterministic environmental impact results obtained through the LCA framework, as well as the results of the previous LCA background report for branch reference mixtures. The comparison results are presented in Table 57.

Table 57. Variation of the deterministic results obtained with the LCA framework against the results of the LCA background report for branch reference mixtures.

Environmental impact	Units	Scenario	Value variation per life cycle module (%)								
			A1	A2	A3	A4	A5	C1	C2	C3	D
Depletion of abiotic raw materials (excluding fossil energy carriers)	kg Sb-eq.	0%RAP	150%	168%	126%	161%	117%	87%	163%	128%	155%
		30% RAP	149%	168%	125%	161%	117%	87%	163%	128%	155%
Depletion of fossil energy carriers	kg Sb-eq.	0%RAP	-200%	-200%	-200%	-200%	-200%	-200%	-200%	-200%	-200%
		30% RAP	-200%	-200%	-200%	-200%	-200%	-200%	-200%	-200%	-200%
Climate change		0%RAP	21%	-9%	-3%	5%	10%	-31%	-15%	26%	28%

Environmental impact	Units	Scenario	Value variation per life cycle module (%)								
	kg CO2-eq.	30% RAP	25%	-8%	-3%	5%	10%	-31%	-15%	26%	28%
Ozone layer depletion	kg CFK-11-eq.	0%RAP	-150%	-11%	-21%	-2%	-25%	-64%	-21%	-7%	-148%
		30% RAP	-153%	-10%	-21%	-2%	-25%	-64%	-21%	-7%	-148%
Photochemical oxidant formation	kg C2H4-eq.	0%RAP	146%	66%	53%	121%	97%	64%	118%	114%	149%
		30% RAP	148%	67%	52%	121%	97%	64%	118%	114%	149%
Acidification	mol SO2-eq.	0%RAP	7%	2%	-30%	14%	-48%	-59%	-17%	-28%	10%
		30% RAP	9%	2%	-33%	14%	-48%	-59%	-17%	-28%	10%
Eutrophication	kg PO4-eq.	0%RAP	-64%	0%	-89%	3%	-54%	-62%	-40%	-33%	-57%
		30% RAP	-64%	0%	-89%	3%	-54%	-62%	-40%	-33%	-57%
Human toxicity	kg 1,4-DCB-eq.	0%RAP	-10%	23%	63%	-57%	77%	43%	-53%	91%	-4%
		30% RAP	-6%	23%	63%	-57%	77%	43%	-53%	91%	-4%
Ecotoxicological effects, aquatic (freshwater)	kg 1,4-DCB-eq.	0%RAP	-142%	-170%	-196%	-164%	-172%	-181%	-165%	-167%	-145%
		30% RAP	-139%	-170%	-196%	-164%	-172%	-181%	-165%	-167%	-145%
Ecotoxicological effects, aquatic (marine)	kg 1,4-DCB-eq.	0%RAP	-135%	-166%	-193%	-164%	-165%	-176%	-165%	-159%	-137%
		30% RAP	-131%	-166%	-193%	-164%	-165%	-176%	-165%	-159%	-137%
Ecotoxicological effects, terrestrial	kg 1,4-DCB-eq.	0%RAP	66%	-3%	-12%	-17%	-22%	-61%	27%	-5%	68%
		30% RAP	69%	-3%	-13%	-17%	-22%	-61%	27%	-5%	67%

Upon careful examination, it becomes evident that large variations exist across most cases. However, attributing these variations solely to differences in the processes employed to model the mixtures falls short of a comprehensive explanation for their significant magnitude.

Further investigation revealed that these variations are primarily driven by different sets of characterization factors. One the one hand, the outcomes derived from the case study are rooted in the CML-IA baseline characterization factors, sourced from ecoinvent and OpenLCA LCIA methods records publicly available via the official OpenLCA downloads platform, Nexus[30]. On the other hand, the results presented in the LCA background reports are computed using the CML-NMD characterization factors[31], which tend to vary significantly from those employed in our study. This situation underscores the critical importance of acknowledging and accounting for uncertainties in LCIA. While the immediate focus of this study lies elsewhere, it is imperative not to overlook the effects of this uncertainties in the future.

Validating the EPMF also requires verifying whether its design effectively meets the requirements that it was intended to do. The formulation of the EPMF and its constituent subcomponents considered a series of design requirements outlined in Chapter 5.1. The way in which the EPMF's design address them

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[30] https://nexus.openlca.org/

[31] Available in the downloads section of https://milieudatabase.nl/ as '*Rekenmethode: Karakteristatiefactoren volgens Bepalingsmethode 1.0*'.

is laid down in Table 58. The results of this verification show that the EPMF meets virtually all requirements, making it adept to treat the design problem specified at the beginning of this document.

Table 58. Requirements verification.

Requirement	Components / sub-components		
	LCA framework	Uncertainty framework	EPMF
Applicability	The framework accommodates all the relevant elements of the pavement systems described by the M&R measures that compose the MJPV.	The framework can capture the uncertainties regarding the pavement system, and the many methodological choices made in its context, as well as the foreground parameters employed to describe it.	See LCA and uncertainty framework columns.
Completeness	The framework considers the environmental categories outlined by the Dutch Standards, and builds upon their system boundaries definition for the context of M&R in the early stages of PM.	The framework identifies and addresses all the relevant sources of uncertainties identified in the LCA analysis, placing the focus on the context of ICO, where information is limited, and uncertainty is high.	See LCA and uncertainty framework columns.
Representativeness	The framework employs Dutch-specific, endorsed default data that is suitable for network-level planning, when information about the project is limited and uncertainty is high. The use of data that is not directly sourced from Dutch-specific databases is justified and further comparable to Dutch-specific data.	The framework characterizes scenario uncertainty with methodological choices variations that are representative of the context. However, parameter variation is characterized using default values that are not per se specific to the context. Collecting empirical data more representative of the context could not be done. However, instructions on how to do it when information and resources are available, including the availability of potential different sources, are delivered.	See LCA and uncertainty framework columns.
Reliability	See uncertainty framework and EPMF columns.	The framework considers all the relevant steps that need to be followed to handle uncertainties in LCA studies and provides a more reliable method for the assessment of environmental impacts.	The framework delivers a reliable platform to calculate the environmental impacts of M&R substantiated by the incorporation of an uncertainty framework.
Clarity / transparency	The methodological framework and the rationale behind its design are clearly laid down in this document, covering several different cases that may arise and instruction on how to address them. Furthermore, the methodology is illustrated with a case study that can further facilitate its further application.	A stepwise approach is employed to present the framework. Like the LCA framework, all the design decisions are justified and explained, and different cases that may arise are addressed. The case study also covers how to approach the uncertainty framework and its connection to the LCA framework, and, as such, facilitates its further application.	The use of the LCA and uncertainty frameworks together present the environmental impacts results and their uncertainties in many ways in which they can be communicated to the stakeholders.

Requirement	Components / sub-components		
Flexibility	The sector and the context of the framework are particularly dynamic, so instructions on how to adapt to new knowledge are included where applicable.	The uncertainty framework provides space for future additions that can improve the analysis or simplify its execution.	The LCA and uncertainty frameworks are flexible to new information. The LCA framework particularly specifies the steps to take in such cases.
Relevance	The framework is designed based on aspects pertaining the MJPV and ICO thus making it directly relevant for their context, including the product and FU definition.	The uncertainties considered in the framework reflect prominent sources of uncertainty for the context of ICO.	See LCA and uncertainty framework columns.
Compatibility	The framework is compatible with the output of IVON2. A structured connection to relevant pavement performance models to estimate PVI is missing. The framework does, however, permits to manually input the data that is required and provides a procedure to obtain it and implement it.	Since the framework is intrinsically connected to the LCA framework, its output is also compatible with IVON2.	The EPMF is compatible with IVON2, but it is not compatible with DuboCalc as the latter does not provide an adequate software platform to implement the methodological framework proposed in this project. Furthermore, it is not directly linked to pavement performance models.
Integration	See EPMF column.	See EPMF column.	The EPMF integrates the knowledge of the RWS in its design, especially regarding the different M&R measures. Consequently, it is suitable for ICO (provided that the use of DuboCalc is not a requirement). It does not directly integrate their PMS or LCA tools.
Complementarity	See EPMF column.	See EPMF column.	The EPMF does not alter the way ICO does operations in any way. Instead, it provides supplementary environmental performance knowledge that can be used to inform the PM decision making processes and to possibly land more sustainable plans.
Scientific soundness	The different elements of the framework are based on official LCA guidelines and scientific literature, including the development of the IRI models and their incorporation to the framework.	The uncertainty framework is based on scientifically sound methods and relevant literature on the subject.	The EMPF has a strong scientific basis backing up its design.

7 EPMF

Chapter 5 of the report presents the designs of the EPMF modules and their validation is described in Chapter 6. This section provides a brief overview of the EPMF design and discusses the digital tool developed to operationalize it and conduct the case study. It also includes specifications for its use and explores its potential for generalizability. Additionally, a design discussion is presented, addressing important aspects such as PVI, comparability, salvage life allocation, and the limitations of the uncertainty analysis.

7.1 DESIGN OVERVIEW

The EPMF provides a comprehensive, structured framework to calculate the environmental performance of M&R considering uncertainties. The LCA framework guides the user through the various stages of the LCA methodology, from defining the system boundaries to interpreting and reporting the results. It considers all the important aspects required to calculate the environmental impacts of pavement M&R measures. Notably, it incorporates the effects of PVI in the calculations through the development of tailored pavement performance models that predict the evolution of roughness in the main road network of the Netherlands, and the use of existing fuel consumption models. In addition, the uncertainty analysis framework leads the evaluation of the uncertainty associated with the input parameters employed in the LCA framework and the methodological choices made by the practitioner, resulting in a more realistic and reliable portrayal of environmental performance. The integration of the uncertainty framework sets the EPMF apart from conventional LCA-based frameworks that do not account for uncertainty, thus making it a more reliable tool for decision-making in PM, especially at the early stages when information is limited, and uncertainty is high.

The EPMF is designed to be flexible and customizable to new relevant information, if the appropriate data, models, and resources that are needed to feed and apply the framework are available. While being tailored to ICO's needs and wishes, the EPMF can also be employed by asset managers, transportation agencies, and other stakeholders involved in the PM process to evaluate the environmental impacts of different M&R measures and plans and inform decision-making. Its generalizability is extensively discussed in Section 7.3.

It is important to emphasize that the EPMF provides valuable information on the environmental impacts of different M&R measures and plans, which can be placed alongside other factors in the decision-making processes of PM (Harvey et al., 2016). While it does not currently offer explicit guidance for comparing different MJPV alternatives or directly steering network-level decisions based on environmental performance, it adds to the decision-making process by providing essential insights. For more detailed information on the current and potential uses of the EPMF, please refer to refer to Chapter 8.

7.1.1 DIGITAL TOOL

In this project, digital tools that demonstrate the feasibility and functionality of the EPMF by operationalizing its components were developed. These include the excel spreadsheets, Python scripts, and LCA models that were instrumental in conducting the case study presented in Chapter 6.1. The tools themselves and their use specifications are provided as supplementary resources. The creation of these tools attests to the EPMF's capability to operate effectively in practice. Moreover, these tools can help to ascertain the viability and value of the EPMF before committing to a real-world implementation.

The excel spreadsheets were developed to enable users to conduct the first steps of the EPMF, such as defining the M&R measure and scenarios to be analyzed and characterizing the input parameters. These spreadsheets were designed to be user-friendly and easy to navigate, with clear instructions and explanations of the various fields and parameters presented.

The LCA models were developed to enable users to generate LCIA results for the M&R measures analyzed using OpenLCA and the LCI database ecoinvent 3.3. These models were carefully designed to ensure that they were consistent with the EPMF, and that they could be easily modified and updated as new data becomes available.

The Python scripts were developed to enable the more complex procedures required by the EPMF, such as the generation of LHS and Sobol samples, LCA model updating, sensitivity analyses, and the computation of the stochastic environmental impacts using an API[32] to connect the LCA model to the Python scripts. These scripts were developed using publicly available packages and libraries to ensure that they were efficient, reliable, and could be easily integrated into existing workflows.

Overall, the development of digital tools was a crucial first step in the operationalization of the EPMF and in ensuring its successful implementation in practice. The process involved careful consideration of the various components of the framework and how they could be integrated to achieve the intended results. It's worth noting that while these tools provide a starting point for implementation, there are many different approaches that could be taken to build upon this foundation, including the development of more sophisticated software. By providing users with these digital tools, the EPMF can move beyond theory and be effectively implemented in practice, which is essential in helping ICO achieve their environmental performance goals. The tools serve as evidence of the framework's capability to function effectively in practice and can be used as a reference point for further development and refinement.

7.2 USE SPECIFICATIONS

The EPMF is meant to inform PM. It offers pavement managers the ability to assess and communicate the environmental performance of their M&R plans. Through its operationalization, ICO can estimate the overall environmental performance of the MJPV, including the effects of uncertainties in the results and the factors that contribute to it. To do so, the environmental impacts of the M&R measures employed in the MJPV can be coupled to the output of IVON2.

It is crucial to clarify that the EPMF is not designed as a Decision Support System (DSS) and does not directly consider the technical and economic aspects of M&R in PM. It does not replace or serve as a direct component of a PMS. However, there is potential for further development of the EPMF to evolve into a DSS and/or be integrated into a PMS. Chapter 8 delves into the specifics of the development and implementation of the EPMF within this context, providing deeper insights into its capabilities and potential future enhancements.

7.3 GENERALIZABILITY

Generalizability refers to the ability of the EPMF to be applied to PM contexts and stages beyond the specified. Ideally, the design of the EPMF should enable its adaptation and application to different PM stages (see Table 3) and contexts (alternative road networks, including regional and municipal roads), while maintaining its scientific soundness and effectiveness. In other words, the EPMF should be flexible and adaptable to different PM needs, while ensuring that it maintains the effectiveness of its environmental performance assessments, increasing its potential for wider adoption and applicability.

Although generalizability was not originally included as a stakeholder requirement, it is important to note that, following scientific research principles, the EPMF was developed with generalizability in mind. While further development and adaptation efforts are required to apply the framework to other contexts, the design requirements and principles that guided the design of the EPMF facilitated the

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[32] APIs (Application Programming Interface) provide a standardized way for software applications to request and receive data or services from other applications. In this case, an API was used to retrieve the sample data from Python, send the data to OpenLCA to calculate the environmental impact of each sample, and send the data back to python for processing.

development of a flexible and adaptable methodology that can ultimately be tailored to different PM needs. Different locations or road jurisdictions may have unique conditions and management practices, and a framework that is too specific or narrow in scope may limit its usefulness and adoption in other contexts. Furthermore, LCA frameworks for infrastructure, such as the EPMF, should not be limited to the early stages. They should be designed to have the flexibility to be adapted and applied in the project-level (Liljenström et al., 2020).

The importance of addressing generalizability lies in the potential for the EPMF to be useful beyond its original application context, maximizing its value and impact, while maintaining its scientific soundness and effectiveness. A framework that is adaptable and can be applied to a variety of contexts has the potential to provide valuable insights into sustainable PM practices not only in other road networks of the Netherlands but also in other countries, and potentially serve as a standard for sustainable PM practices globally. This section delves into the topic of generalizability and explains how the EPMF can be adapted to different needs and contexts.

7.3.1 HOW CAN THE EPMF BE ADAPTED TO DIFFERENT PM NEEDS?

In general, the rationale behind every design decision, as well as the design process, specifications and suggestions laid down in Chapter 5 set a solid basis to translate the use of the framework to other PM contexts and stages. In other words, enough information is provided in this document to make the EPMF suitable to other PM needs. This section discusses some of the potential adaptations that would need to be made to the EPMF to make it suitable for other PM needs, providing an outlook on the potential for generalizability of the EPMF to other PM stages and road networks beyond the Dutch main road network.

In the LCA framework, the goal and scope definition, as well as the LCI, should be adjusted. In theory, the goal, product definition, product cases, analysis periods, system boundaries, impact categories and data requirements would need to be modified to reflect the new contexts accordingly. The uncertainty analysis framework, on the other hand, would likely see key changes in the identification and characterization.

In practice, most of the LCA framework scope and goal definitions will hold across different PM contexts and stages. Small adjust may be made to reflect the context in which the EPMF will be implemented, e.g., completely different location, or a later PM stage. The product definition can change if, for example, other M&R measures, or types of asphalt layers (e.g., base, and sub-base) and mixtures are included. For example, the branch reference mixtures would not be the best pavement materials standard for later PM stages or contexts different than the Netherlands. In terms of product cases, an update would be required if new M&R measures that do not fit the options that are offered in this document are incorporated into the analysis. The system boundaries would likely stay the same, as the life cycle of pavement M&R between pavement systems is constant regardless of the context. Potential additions are the incorporation of more use phase mechanisms into module B, or a change in the notation used to name the modules. The environmental impact categories and weighting methods would have to be adjusted to comply with the LCA standards, norms and, if available, the PCRs of the context. Impact assessment methods other than CML and PEF may be required in other contexts, and the use of MKI would not be applicable outside of the Netherlands. Following, data requirements would likely be the section with the greatest changes. In the Netherlands, for example, if the framework were to be applied in later PM stages, the data requirements would now refer to supplier- and project-specific data. Similarly, in other contexts, different data classifications may hold, and different data sources would be sought, and the framework would have to be adapted to capture them. It is important to note that just as this framework was based on the official documents and guidelines for the Dutch context (NL-PCR and Determination Method), adapting the EPMF to contexts other than the Netherlands may require the executor to employ the norms, documents and guidelines that are valid for their context.

The empirical quantity value parameters to model the life cycle processes in the LCI must be adapted to reflect the new application context. Representative LCI data comparable to that provided in the LCA framework would be sought. Since the data must reflect the new context, it must be obtained from sources that are pertinent to that context. The new data requirements outlined in the modified LCA framework would guide the collection of LCI data and ideally point to the data sources from which it can be retrieved.

The steps for uncertainty identification and characterization in the uncertainty framework would be the subject of adaptations to make it suitable for other PM needs. Data adjustments, particularly pertaining scenario uncertainty, would be necessary. Scenarios would be required to reflect the particularities of the adapted LCA framework specifications. Perhaps a wider range of scenarios would need to be defined in response to larger scenario spaces, or to other key choices and assumptions to be made by the LCA executioner. The baseline scenarios would also need to be adapted to the context needs. For parameter uncertainty, extending the additional uncertainty methodology to capture the uncertainty of the intermediate flows may be required (as mentioned in Chapter 5.3.2.1), particularly in contexts where appropriate LCI background databases are lacking. It is important to note that the characterizations assigned to uncertain parameters or scenarios, whether in the form of minimum/maximum values or PDFs, should be regularly reviewed and adjusted to better align with the specific context in which the EPMF is being applied.

Beyond the context of pavements, the EPMF's underlying approach can be a valuable reference for other infrastructure domains seeking to develop their own environmental performance assessment frameworks. While system boundaries would need to be adapted to reflect the unique characteristics of each infrastructure domain, the fundamental life cycle concept of the EPMF would remain applicable as all infrastructure systems are in essence civil constructions.

7.4 DESIGN DISCUSSION

The EPMF is a stochastic LCA-based methodological framework developed to support the early stages of PM of the main road network in the Netherlands. It provides stakeholders with valuable insights into the environmental performance of different M&R measures. While its comprehensive design is a step in the direction towards sustainable PM, the framework has some aspects and limitations that need to be addressed.

In this section, the implementation of certain features of the EPMF design are discussed, including the incorporation of PVI, comparability and compatibility issues, the treatment of salvage life allocation, the limitations in the treatment of uncertainties in the framework, and the full scope of a M&R plan. By examining these aspects of the EPMF, its strengths and weaknesses can be better understood and strategies to improve the framework for future applications can be identified.

7.4.1 UNRAVELING THE APPROACH TO PVI

7.4.1.1 PVI APPLICABILITY

The EPMF accounts for PVI in the system boundaries of M&R, which sets it apart from current LCA tools and guidelines employed by the Dutch pavement community However, it only does so for rehabilitation measures. It is difficult to assess whether maintenance treatments can improve pavement roughness and cut extra fuel consumption due to increased RR based on the information available for this project[33].

Due to this reason, it was assumed that the application of maintenance treatments had no effect on RR, and PVI was excluded from their evaluation. Module D would be able to capture the PVI benefits of the treatment application if this were not the case, by projecting the extra fuel consumption savings over the remaining intended service life of pavements prior to the application of maintenance. To complete this task, the system boundaries of maintenance measures should be adjusted to accommodate module D.

7.4.1.2 PVI DATA AND LINK TO PAVEMENT PERFORMANCE MODELS

The inventory data currently employed to account for PVI in the EPMF is derived from performance models developed for this project, which are limited by the training data and methods that support them. The RWS does not currently employ nor has developed official IRI and MPD models, let alone RR and fuel consumption related models. While the models developed, sourced, and employed to address PVI within the project provide a foundation for applying the EPMF, it is important to recognize that they serve as an initial reference and should not be regarded as conclusive or the better benchmark.

It is important to keep in mind that the value of the EPMF is directly proportional to the data that feeds it. In other words, the quality of the output is directly determined by the quality of the input. As a result, by developing, revising, and refining the PVI models, as well as updating the LCI data on a regular basis, the EPMF output can be substantially improved.

Furthermore, pavement deflection was left outside the scope of the PVI effect calculations due to a lack of reliable data and models to estimate its effect on RR. However, it is important to consider the effect of deflection in RR when, and if, models to conduct this task become available, especially in the context of HDVs and higher temperatures (van Haaster et al., 2015).

7.4.1.3 PVI APPLICATION WIDTHS

Due to the variation in deterioration rates between lanes and the assignment of analysis periods, the current framework suggests only considering PVI in carriageway-wide measures. Although suggestions for including PVI into lane-wide measures are presented, more research is required to accurately capture PVI in the analysis and account for PVI effects' variations between lane- and carriageway-wide measures.

7.4.1.4 PVI SCENARIOS

After emphasizing the importance of PVI in evaluating the environmental impacts of pavement M&R, it may appear contradictory to design scenarios that exclude PVI from the system boundaries of rehabilitation measures. Incorporating PVI into the analysis, however, may prevent a comprehensive review of how other life-cycle processes impact the results.

The dominance of PVI in both the environmental impacts and the uncertainty can make it difficult to examine the role of the other variables in the results. The environmental impacts of PVI are significantly greater compared to other processes, to the extent that they overshadow the effects of other activities

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[33] The reduction in RR following maintenance treatments is a possibility, but the available information is insufficient to support this claim. Similarly, the effects of applying a thin layer of ZOAB, i.e., ZOABDI, on RR are not well-studied. Although there are measurements available for IRI and MPD on surfaces treated with these materials, the data exhibits significant variability, making it difficult to draw reliable conclusions. Further research is needed to assess the potential RR reductions that can be achieved with these treatments.

throughout the entire life cycle. To gain a clearer understanding of the impact of these other life-cycle processes, it can be beneficial to define and analyze model domain scenarios hat specifically exclude PVI from the system boundaries.

7.4.1.5 BEYOND PVI: OTHER USE PHASE MECHANISMS

Although the EPMF includes PVI in its analysis, it overlooks other use phase mechanisms, such as Albedo, which has been proven to be exert a large influence in the uncertainty of the results (Gregory et al., 2016). To address this limitation, the expansion of the use phase system boundaries in the future is recommended.

7.4.2 EXPLORING THE FEASIBILITY OF MEASURE COMPARISON

To address the issue of limited comparability between different M&R measures, it is important to consider the purpose and nature of each type of measure. Rehabilitation measures, which involve the full or partial replacement of the pavement system, have a clear impact on service life and can be compared within their own category. However, it is not that simple to compare rehabilitation measures to maintenance ones. The purpose of maintenance is to preserve and improve pavement condition to delay the onset of extensive damage before rehabilitation is applied. Due to the inherent different purpose and the uncertainty behind the influence of maintenance on pavements' service life, it is difficult to compare one to the other.

As previously mentioned, enabling more meaningful comparisons between M&R measures may require that the EPMF is modified to include module D. The benefits and costs outside the system boundaries could capture the benefits of performing maintenance prior to the next rehabilitation. Doing so would demand information on the structure being intervened, the net environmental savings obtained through roughness improvement, and the extra fuel consumption due to the anticipated service life increment ensued by performing maintenance. This approach would enable a more accurate assessment of the environmental benefits that could be attained by performing maintenance measures and provide a more adequate basis for comparison with rehabilitation.

In addition, it is important to consider the specific elements of the pavement structure and materials when assessing the impact of different M&R measures. The impact of measures may vary depending on the service lives of each layer, and disaggregating the impact into individual elements of the pavement system can facilitate more accurate comparisons. However, comparing lane- and carriageway-wide measures is still challenging due to the different nature and service life implications of these measures. It may be necessary to evaluate them separately or develop additional approaches to enable comparison across these different types of measures.

Another important consideration revolves around uncertainty comparability. While the EPMF provides guidelines on how to communicate uncertainty results, it has yet to address the active and formal comparison of these uncertainties. If the goal is to use uncertainty metrics to make claims about the relative performance of different M&R measures or scenarios, discernibility analysis offers a structured approach. Discernibility analysis provides probabilities of one alternative outperforming another, which can support claims of superior environmental performance among M&R measures and scenarios (Igos et al., 2019). However, further investigation is needed for the implementation of discernibility analysis in this context.

7.4.3 SALVAGE LIFE ALLOCATION

Salvage life allocation can be an important consideration when evaluating the environmental performance of M&R measures (Mentink, 2021), and the EPMF currently does not account for it. The issue of salvage life allocation arises when a rehabilitation cycle is performed before a pavement reaches intervention levels due to, for example, optimized programming. In this case, the benefits of performing rehabilitation in terms of PVI effects must be captured in module D, corresponding to extra fuel consumption avoided in terms of the years saved. To implement salvage life allocation, information regarding the age, structure and condition of the pavement system replaced must be accessible.

7.4.4 EXPLORING THE BOUNDARIES OF THE UNCERTAINTY FRAMEWORK

7.4.4.1 SCENARIO ANALYSIS

The EPMF is designed to address various types and sources of uncertainty in the analysis. However, including uncertainties in the analysis can be computationally expensive, especially when exploring different scenarios. PCRs provides standardized guidelines that limit the decision space in pavement LCA and reduce uncertainties in the analysis (Gregory et al., 2016). However, there are still some relevant decisions to be made in the context of the EPMF despite the existence of the NL-PCR. These are documented and addressed in the approach, but a systematic method for identifying the most uncertain scenarios is still lacking.

In the future, methods proposed by Gregory et al., (2016) and Jaxa-Rozen et al., (2021b) for scenario discovery should be implemented to better understand the impact of the most significant methodological choices on the results that can provide valuable insights on how to further reduce the complexity of the analysis.

7.4.4.2 ASPHALT QUANTITY

One prominent uncertainty that the EPMF overlooks is the quantity of asphalt used in the construction process. The serrations and the practical asphalt thickness that are considered in the definition of the M&R measures in the RWS (GPO, 2022) highlight the need for stochastic treatment of asphalt quantity. In the framework, the difference in asphalt quantity is partially captured in the definition of the model domain scenarios that refer to the physical boundaries of the measures, although these are rather important when looking at measures in a broader, overarching fashion. To fully capture the uncertainty involving asphalt quantity, the alternative FU definition can be modified to include a certain coefficient of variation. The same exercise can be done to consider extraordinary patching, a construction activity that was disregarded by the framework.

7.4.4.3 ASPHALT DURABILITY

Asphalt durability is captured in the definition of different analysis periods based on the lane that is being treated. These analysis periods can be varied as scenarios. However, this approach doesn’t capture the inherent variability of the expected life spans of different asphalt layers. The uncertainty due to variability is an important consideration that should be explored in the future (see Abed et al., 2023; Godoi Bizarro et al., 2020).

7.4.4.4 PARAMETER UNCERTAINTY CHARACTERIZATION

Characterizing parameter uncertainty in terms of additional and basic uncertainty, following the ecoinvent method (Weidema et al., 2013), is an approach that is generally accepted by LCA community. The EPMF follows this approach and conducts the case study accordingly. Note that the use of the default basic uncertainty values provided by the ecoinvent method should only be employed in the absence of empirical data. In order to get more reliable and representative results from the uncertainty analysis, it is recommended to gather empirical data that can better represent basic uncertainty. Similarly, the generic uncertainty factors provided to characterize additional uncertainty using the so-called pedigree approach should be revised and improved when possible (Ciroth et al., 2016; Muller, Lesage, & Samson, 2016)

The characterization of intermediate flows uncertainty as an extension of additional uncertainty values (Gregory et al., 2016) is instructed in this framework. This, however, is only relevant when employing proxy processes. In this framework, the most notable example of intermediate flow uncertainty concerns the modelling of the Unimog machine in module A5 of surface roughening maintenance measures, given the information retrieved. In the lack of more specific data, the process is defined using proxy construction machinery profiles and data provided in the NL-PCR (Van der Kruk et al., 2022).

7.4.4.5 LCIA UNCERTAINTY

It is important to note that while the EPMF considers multiple sources of LCI uncertainty, it does not account for uncertainties in the LCIA. Considering these uncertainties was not part of the scope of the project given that they pertain to a much larger LCA picture than that related to the road pavement M&R scope defined in this project. However, uncertainties in the LCIA, particularly on the MKI values, are high and require further exploration in future studies. The uncertainty in the MKI values is a prominent uncertainty that cannot be overlooked. although the verification results in Chapter 6.4 suggest that uncertainties in the characterization factors defining the impact categories can considerably affect the outcomes of the analysis.

7.4.4.6 SENSITIVITY ANALYSIS CONSIDERATIONS

It is recommended that the sensitivity analysis in this framework is conducted using the Extra Trees and/or PAWN GSA techniques due to their ability to provide similar approximations to total Sobol indices in a significantly shorter amount of time, provided that the calculation of higher order Sobol indices is not necessary. Moreover, when dealing with high dimensionalities, screening techniques can be employed to reduce the random parameter input space and enhance the overall quality and efficiency of future uncertainty analyses.

7.4.4.7 CHANGES AND UPDATES TO CHARACTERIZATION VALUES

Like the data of the LCI, the values employed to characterize both parameter and scenario uncertainties should be modified when new information is available. This could be due to various factors such as the introduction of new default values, updated versions of the NL-PCR, or more recent studies on branch reference mixtures in LCA. Additionally, as the PM cycle progresses, new empirical uncertainty values or other relevant information may become available. Therefore, it is necessary to create and analyze new samples to obtain updated uncertainty values.

To streamline the process and reduce computational time, screening methods can be employed. These methods focus on reducing dimensionalities by considering only the most uncertain parameters for further updates. Advanced GSA techniques, (Jaxa-Rozen et al., 2021b; Sudret, 2008; Sudret & Mai, 2018), can be utilized to simplify the calculations without compromising the accuracy of the results.

In addition to screening methods, surrogate models, and model updating techniques can be employed to manage the complexities of uncertainty analysis. Gaussian process regressions and Bayesian approaches offer efficient ways to handle uncertainty by developing simplified models based on available data (Dai et al., 2022; Lo et al., 2005; Seshadri et al., 2019; Zhou et al., 2021). These techniques can be utilized in place of computationally expensive simulations, providing a more efficient architecture for uncertainty analysis. By leveraging these techniques, the process of updating uncertainty values becomes more manageable and allows for timely adjustments as new information emerges throughout the PM cycle. The overarching goal is to strike a balance between reducing computational burden and maintaining the accuracy of the results in uncertainty analysis within the context of the EPMF.

7.4.5 UNLOCKING THE COMPLETE SCOPE OF M&R PLANS

The EPMF is designed to assess entire M&R plans, particularly as built-up by ICO. It considers M&R plans as a comprehensive strategy consisting of multiple individual M&R measures for the main road network. In principle, applying the EPMF to the M&R plan scale is already possible. A direct connection can be made between the environmental impacts resulting from each measure along with their uncertainty, considering the scenarios defined by the executioner, and the output of the MJPV.

However, challenges arise in aggregating the impacts of individual measures to provide a total estimate for the entire plan. Simply summing up the impacts may oversimplify the information, reducing it to a single number without considering the distinct impacts of different measures. Furthermore, compatibility issues hinder the reflection of net costs and savings associated with the plan. The absence of clear links to pavement performance models and other relevant information further complicates the comprehensive network analysis required for calculating net costs and savings.

Disaggregating the total impacts into life-cycle phases, specific measures, or pavement structures could be a viable option. Ideally, the MJPV should include all available formats, enabling analysis at the measure, total, and disaggregated levels. However, aggregating uncertainties may still pose similar challenges to those related to the total estimates.

Another significant challenge is addressing uncertainty within the accumulated impacts. One potential approach to aggregate uncertainty is to treat the combination stochastically, resulting in a new probability distribution for the aggregated results. However, implementing this approach adds complexity to the analysis and demands additional resources. Evaluating the feasibility and value of this approach is crucial before proceeding with it.

In summary, substantial work is required to effectively account for aggregated uncertainty and successfully transition from the measure scale to the plan scale. By addressing the challenges related to aggregating impacts, incorporating net costs and savings, establishing clear links to pavement performance models, and effectively managing aggregated uncertainty, the EPMF can provide a more comprehensive assessment of the full M&R plan scope.

8 DEVELOPMENT AND IMPLEMENTATION PLAN

The EPMF is a comprehensive and robust LCA-based methodological framework that, when operationalized, can provide pavement managers with valuable insights into the environmental impacts of M&R plans. It was designed according to the needs of an LCA framework tailored to early PM stages, where network-level M&R plans are developed. Its development was commissioned by ICO as part of this EngD project, driven by the recognition of the importance of addressing environmental concerns and seeking to align with the broader sustainability ambitions of the RWS and the pavement sector.

PM is a complex and dynamic socio-technical system where interconnected social and technical elements mutually shape and influence each other over time. A successful integration of the EPMF in PM, specifically in ICO's operations, requires a comprehensive understanding of the interactions among these elements. By recognizing the potential challenges and opportunities that arise from these interactions, ICO and the RWS can devise proper strategies to ensure an effective development and implementation of the framework.

The EPMF exists as part of the PM system, which is a component of the larger main road pavement system. Table 59 provides an overarching view of the system, including the temporal and hierarchical dimensions of PM and the EPMF. The historical context reflects conventional approaches that did not consider current environmental concerns. Modern landscape developments and regime changes have spurred a shift in perspective, which is captured in the sustainable road pavements transition pathway driving the evolution of the Dutch pavement domain (Rijkswaterstaat, 2020, 2022b, 2022a).

Table 59. Nine-window diagram for sustainable PM.

Conventional main road pavements	Sustainable main road pavements	Future sustainable main road pavements
Conventional PM	Sustainable PM	Future sustainable PM
IVON2 (PMS), pavement performance frameworks and models, cost-benefit analysis (CBA) techniques, decision trees (optimal intervention strategies), optimization techniques, etc.	EPMF. *Other current examples:* DuboCalc, MKI, CO2 ladder, green procurement strategy, etc.	DSS and PMS for sustainability-enhanced M&R planning (MCDA, MOO), data-driven modelling and forecasting, prospective LCA frameworks, smart detection/prediction/ monitoring technology, multifunctional road surfaces (asphalt surfaces as heat and electricity generators), artificial intelligence approaches, climate-neutral and 100% circular roads, etc.

The commission and development of this EngD project and the EPMF is a response to the ongoing sustainability transition. Exploring socio-technical dynamics and interactions at multiple system levels is essential to understand the EPMF's success factors. This chapter explores the development and implementation potential of the EPMF in PM, beginning with ICO and progressing beyond. First, it delves into the socio-technical context of PM and the broader sustainable road pavements transition pathway. Thereafter, it looks at the role that the EPMF can play in (1) informing and (2) supporting network-level decision-making in PM, as well as its maturity in respect to these functions.

Furthermore, this chapter examines the present and future capabilities of the EPMF within the wider context of the sustainable road pavements transition pathway, employing a multi-level perspective to sketch different socio-technical pathway scenarios. It incorporates practical findings gathered from the focus group conducted as part of the EPMF validation tasks outlined in Chapter 0. The action perspectives presented herein provide valuable guidance for effectively operationalizing the EPMF, considering varying abilities and capacities and driving progress towards more sustainable road pavements.

8.1 SUSTAINABLE ROAD PAVEMENTS TRANSITION PATHWAY

The Dutch context is actively engaged in a transition towards sustainable road pavements, driven by the pressing realities of global warming and climate change. Foreseeing this shift has been a collaborative effort between the national government and the RWS, as well as other relevant stakeholders of the regime, further described in Table 60 (Rijkswaterstaat, 2020, 2022a, 2022b). Together, they developed a roadmap for sustainable road pavements that (1) delivers an overview of the transition context, including the scope of the sustainability challenge and the intricacies of the sector, and (2) outlines short-, medium- and long-term visions for the implementation of innovations aimed at achieving sustainability goals and supporting the transition (Rijkswaterstaat, 2022b).

Table 60. Stakeholder within the sustainable road pavements transition. Adapted from Rijkswaterstaat, (2022b).

Stakeholder	Role and responsibilities	Examples of actors
RWS	Translate sustainability ambitions into goals, drive innovations, draw up sustainability requirements, and work towards the national roads' sustainability targets.	RWS: GPO, ICO, PPO, W&G, etc.
Other government organizations / road authorities	Retaining the long-term sustainability urgency, facilitating decision-making resources, collaboration via buyer groups, foster innovation programs (bio-based asphalt & sustainable asphalt plants), knowledge exchange.	RWS, provinces, municipalities, umbrella organizations (e.g., Waterboards union), PIANOO, etc.
Contractors	Execute projects, comply with environmental requirements, invest in development and innovation, and cooperate to regulations and knowledge sharing.	Ballast Nedam, BAM, Boskalis, Dura Vermeer, Heijmans, KWS, Strukton, Van Gelder, etc.
Knowledge institutions	Develop and disseminate road construction and sustainability knowledge, help monitor the transition.	UT, TNO, CE Delft, other Dutch universities, CROW, Asfalt-Impuls, etc.
Regulatory bodies	Adjust and develop technical, environmental, and procurement regulations accordingly.	Asfalt-Impuls, CROW, NEN, PIANOO, etc.
Other market parties	Developing and supplying alternative additives and raw materials, knowledge development.	Chaplin (bio-based materials), ESHA, Latexfalt, Cargill, etc.

Driven by evolving needs and landscape developments, the socio-technical system of sustainable road pavements (Figure 37) has witnessed various innovations driven by the sustainability transition arise. Within the Dutch main road network, sustainable road pavements are part of a cluster of elements that comprise the production system and industry structure, markets and user practices, regulation and policies, culture and symbolic meaning, road infrastructure and traffic systems, and the PM network (Geels, 2004, 2005). Recent years have seen several innovations emerge at the production system and industry structure level. Parallelly, environmental assessment tools, namely the CO2 ladder and DuboCalc, have emerged at the PM network level to support green procurement and encourage contractors to deliver more sustainable pavement project designs (Van Geldermalsen, 2020). The RWS, knowledge institutes, contractors, and other market parties play important roles in driving the development and implementation of these innovations. While the sustainable road pavements roadmap acknowledges key innovations contributing to the sustainability transition, the strategy outlined therein overlooks innovations at the PM network level that could capture the functionalities of the EPMF[34].

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[34] The roadmap included a M&R planning optimization measure comprising the use of big data for improved service life forecasting and scheduling of M&R interventions to achieve environmental impact reductions at the network-level. In principle, the EPMF seeks may seek a similar goal, but via environmental performance assessments instead of big data.

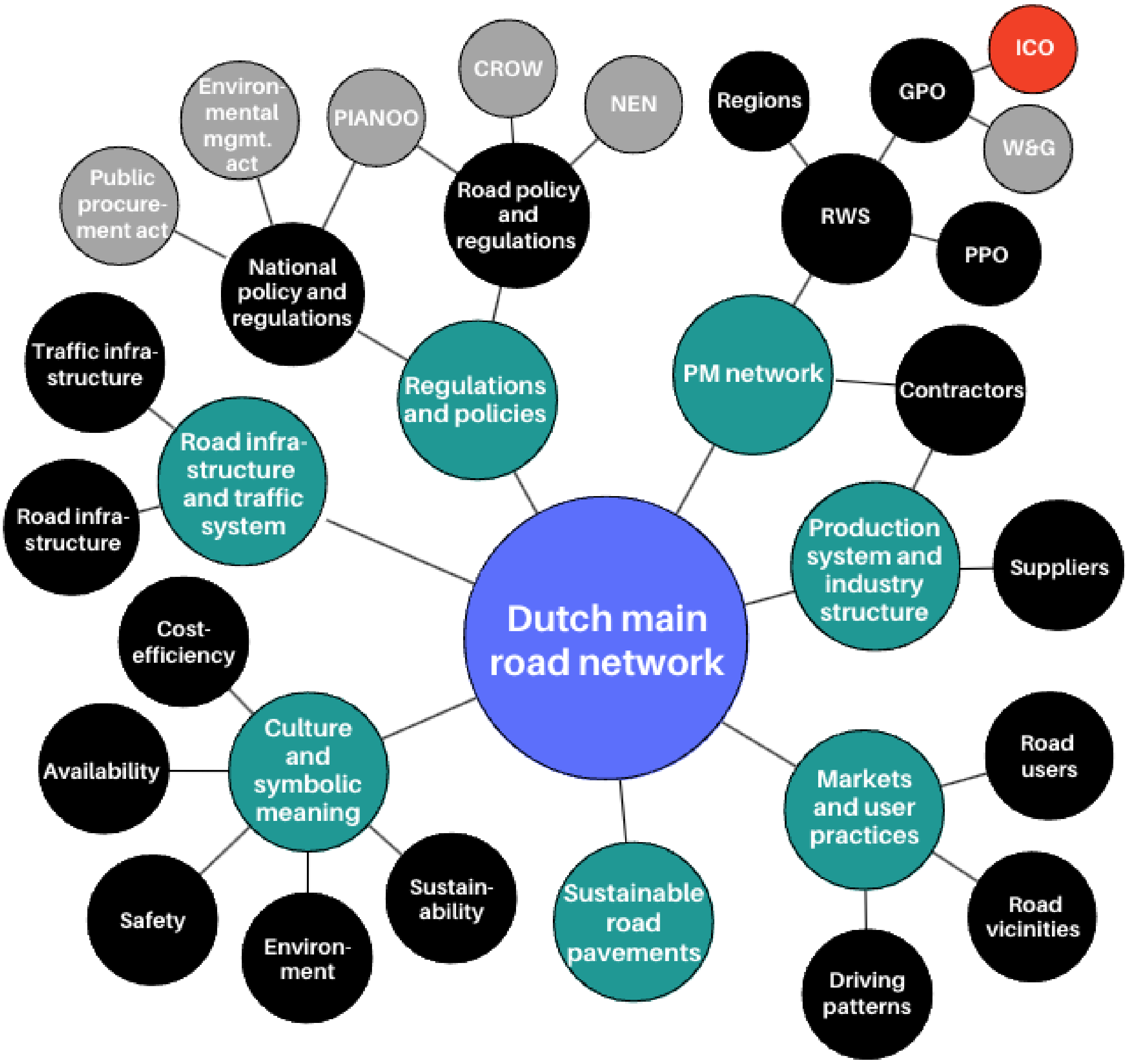

Figure 37. Sustainable road pavements socio-technical system for the Dutch main road network.

The sustainable road pavements roadmap primarily relies on the development and implementation of niche innovations at the production system and industry structure to improve sustainability in the sector. These innovations target improved design and execution[35] including life-extension treatments (i.e., maintenance measures), improved asphalt durability, increased use of RAP in asphalt mixtures, cleaner production methods, and the adoption of bio-based binder materials. While they certainly play a role in enhancing the sustainability of road pavements, they also come with their own set of challenges and feasibility considerations. For instance, bitumen, despite its environmental burden, is a residual product of oil refineries that could become a waste product if not used for asphalt production (Rijkswaterstaat, 2020). Likewise, the interviews revealed that the availability of RAP is significantly restricted, posing difficulties for contractors aiming to scale up its use in large projects. However, the

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[35] Measures towards a more sustainable use of road construction equipment, both machinery and vehicles, are comprised in the *Sustainable Road, Dike, and Rail Equipment Transition Path*. The roadmap emphasizes the reduction of emissions associated with construction equipment use through various strategies. Examples include transitioning from fossil fuel-powered equipment to alternatives such as electric construction equipment, hydrogen-powered machines, and/or machinery operating on fixed grid connections, as well as optimizing the logistics of material flows (Rijkswaterstaat, 2022a).

sustainable road pavements roadmap fails to consider alternative approaches that prioritize the enhancement of planning, policy, and decision-making processes in PM[36], which are not limited by the same physical constraints as the other innovations, and offer considerable opportunities to achieve substantial environmental gains (Liljenström et al., 2020).

The transition strategy outlined by the sustainable road pavements roadmap, unlike initiatives undertaken in road agencies elsewhere[37], essentially neglects measures that seek to enhance network-planning in PM. Integrating environmental performance into early planning offers a unique opportunity to reduce the environmental impacts of pavements at the network-level, which gradually closes as the PM cycle progresses (Liljenström et al., 2020; Miliutenko et al., 2014). Moreover, the EPMF is at conflict with the deliberate decision to leave PVI and RR offsets out of the roadmap's scope, which are central to more sustainable M&R plans that seek to mitigate the environmental impacts of pavements throughout their entire life cycle (Harvey et al., 2014; Liu et al., 2022; Santos et al., 2022). The absence of these elements from the roadmap undermines the potential contribution of the EPMF and LCA frameworks alike to the sustainability transition in the pavement sector, which constrains not only their overall influence but also the reach and effectiveness of the broader sustainability strategy.

To meet the RWS' 2030 sustainability goals, it is essential to prioritize maximum incremental sustainability, aiming for the highest possible level of sustainability within the existing regime (Rijkswaterstaat, 2020). However, following the current approach and relying solely on project design and execution improvements is insufficient to achieve this objective. To effectively maximize environmental impact reductions in the pavement sector, it is necessary to address the early stages of PM and leverage the use of LCA therein. By doing so, environmental gains can be achieved early on, leading to more effective sustainability outcomes.

The EPMF is specifically designed to accommodate the LCA needs of ICO in early PM, but it risks losing significance if its potential capabilities are not fully acknowledged and leveraged. Integration into the broader context of the sustainability transition is crucial to prevent this from happening. Thus, positioning initiatives that capitalize on the environmental LCA of pavements in network-planning within the sustainable road pavements transition pathway is needed, which requires acknowledgement and commitment beyond ICO. To assert the EPMF's value it is important to determine how it may be effectively incorporated into early PM, evaluating its maturity in this regard, and defining the actions and resources required to do so considering its broader socio-technical context. By addressing this, the distinct role that the EPMF can play in network-planning and PM can be established, and efforts can be devoted to its further development and successful deployment, ensuring that its potential contributions to the sustainability transition are fully exploited.

8.2 ANALYSIS OF THE SOCIO-TECHNICAL SYSTEM OF PM FROM THE EPMF'S VIEW

The EPMF is embedded in the socio-technical system of PM, which functions as part of the sustainable road pavements socio-technical system for the Dutch main road network. The current application of sustainability innovations within the PM network is centered around DuboCalc, the procurement tool of the RWS, which, as the EPMF, relies on the LCA methodology. Research has been conducted on the potential extension of DuboCalc to other stages of PM (Mentink et al., 2020), but no conclusive actions to do so have been defined yet. It is essential to recognize that DuboCalc predominantly targets procurement activities at the project-level, while the EPMF is explicitly tailored to meet the network-

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[36] Additionally, the sustainable road pavements roadmap explicitly excludes measures pertaining to the use of control of PVI effects, traffic management, and NOx and noise reduction targets.

[37] The FHWA's roadmap for PM in the US includes a collection of actions and innovative measures aimed at advancing PM practices. One key action is the development of a framework that integrates costs and environmental LCAs into PM, enhancing the use of PMS to support planning demands. This action is described as a long-term research initiative with a relatively high budget allocation (K. Zimmerman et al., 2022).

level demands, thus serving different purposes and addressing distinct needs (Butt et al., 2015). This suggests that, despite some apparent parallels, their socio-technical elements and interactions will show considerable differences and call for different approaches.

Figure 38. Socio-technical system for Dutch PM with an emphasis of the elements related to the EPMF.

Understanding the various socio-technical elements that influence the EPMF from a user perspective, covering its development, incorporation and use (Geels, 2004), is required to understand and plan its prospective development and implementation in ICO and PM. Figure 38 showcases the socio-technical system of PM, explicitly mapping the lower-tier elements that are relevant to the EPMF. Following, the main elements and their influence over the EPMF are examined:

1. ***Management network***: Further developing, updating, and maintaining the EPMF is a task that the RWS and ICO, as the commissioners and final users of the EPMF, must undertake. The participants of the focus group recognized that appointing someone to oversee the maintenance and operation of the framework is necessary for successful use and implementation. This responsible party must possess the knowledge background requirements that are necessary to understand the underlying principles behind the design of the framework as well as its operational needs. Participants in the focus groups emphasized that certain expertise, which not everyone possesses, is necessary for successfully applying the EPMF. Furthermore, the management network must oversee the continuous development and improvements of the framework, as well as in managing its connections with other PM infrastructure. Successfully managing the EPMF requires organizational commitment and endorsement.

2. ***Production system and industry structure***: The successful adoption of the EPMF relies on the availability of necessary resources and expertise. Collaboration with experts and external parties is essential for further developing and operating the framework. This includes access to data resources from entities like NMD, ecoinvent, NL-PCR, etc., some of which may require additional financial and/or technical resources. Therefore, it is of the utmost importance that the EPMF addresses any potential compatibility challenges and issues with the production system and industry structure that may emerge, notwithstanding the results of the focus group indicating that there are no fundamental compatibility issues impeding its local implementation.

3. ***User practices***: Implementing the EPMF requires integrating it into the working protocols of the RWS and ICO. This entails adopting the assessment methodology outlined in the framework and ensuring its integration into early PM operations and beyond. The focus group revealed that confining the use of the EPMF solely to ICO's operations could diminish the value of the framework. Ideally, the results produced by the EPMF should be of interest for all the actors involved in the PM cycle, and its use should be eventually extended to the rest of the stages. This requires a continuous flow of environmental performance information throughout the PM cycle that is timely adjusted as new data emerges or plan changes occur. Effective stakeholder engagement and collaboration are essential to accomplish this, given the diverse interests and objectives involved in PM. Note that given the complexity and computational demands of the current uncertainty framework of the EPMF, careful development strategies for its widespread integration in PM should be devised, as adjusting the results requires conducting the entire analysis again, which may pose challenges in terms of organizational capacities and resources. Therefore, it is essential to prioritize the refinement of the uncertainty methodology to enhance its efficiency and feasibility within the given constraints.

4. ***Symbolic meaning***: While sustainability is a fundamental principle of the EPMF, it is important for the framework to align with other values associated with PM and sustainable road pavements. This requires compatibility with a broader multidimensional perspective, either by coexisting alongside cost and technical assessments, or by striking a balance between them. Currently, the EPMF is designed to exist alongside the conventional PM objectives sought by ICO, as deemed satisfactory by the focus group participants. However, in the future, achieving a balance among these values may contribute to wider acceptance of the framework within the broader context of PM, upgrade its functionalities and increase its value.

5. ***RWS and ICO infrastructure***: The EPMF must coexist with the current PM infrastructure, particularly alongside IVON2, the employed PMS for M&R network-level planning. Ensuring compatibility with ICO's infrastructure is vital to uphold the EPMF's value. The current design of the EPMF allows it to function as an add-on that is compatible with the output of IVON2, which yielded positive reviews by the participants of the focus group. However, in the long run, integrating it into the PMS as a permanent component may be a favorable option, if feasible. In any case, the results provided by the EPMF must remain compatible to the MJPV's output structure. Note that the focus group results indicate that while compatibility with PM infrastructure other than that employed by ICO (e.g., DuboCalc) is not strictly required for its operationalization in early PM, it is desirable for several reasons. Seeking this compatibility in the long term can help harmonize PM organizational practices, prevent interoperability issues, and streamline the overall process, particularly when the EPMF is implemented beyond ICO's action field.

6. ***Regulations and policies***: The EPMF, being based on the LCA approach, must adhere to relevant official LCA standards, including the NL-PCR, Determination Method, and European norms. Additionally, it must align with the broader RWS and the specific ICO regulations and

standards, such as SLAs and performance indicators (PINs[38]), OBR directives, and documented plans and agreements guiding the sustainable road pavements transition pathway. Collaboration with actors in the management network as well as in the production system and industry structure is essential for keeping the EPMF up to date with these regulations. Note that the focus group findings highlighted the importance of incorporating the EPMF guidelines into the OBR to consolidate its use within the organization and enable its systematic operation. This inclusion requires endorsement and collaboration across the entire PM process.

To gain a deeper understanding on how these elements and dependencies may evolve and influence the EPMF, it is necessary to first demarcate the specific role of the framework within ICO and PM. This entails assessing its maturity in fulfilling that role and exploring the various socio-technical pathway scenarios that may arise when seeking higher maturity levels, along with their reciprocal shaping effects. By examining these aspects, potential enablers, barriers, and needs associated with the EPMF development and implementation can be explored.

8.3 THE ROLES OF THE EPMF IN EARLY PM

Although the EPMF was specifically designed to address the needs of an LCA framework in the early stages of PM, transitioning from theory to practice poses concrete challenges. The validation of this project has confirmed two important things: (1) the feasibility of operationalizing the EPMF at a small scale, and (2) its ability to provide environmental performance insights for M&R measures relevant to the early stages of PM, including PVI effects and uncertainties. However, to make a formal commitment to its further development and implementation, the RWS and ICO need to understand how the EPMF could systematically assist their PM operations. This entails envisioning how its development and implementation would look like, identifying what it would require, and assessing the prospective benefits it would bring.

LCA-based frameworks, such as the EPMF, can assist early PM in several ways. In its most basic form, LCA can provide valuable information to pavement managers regarding the environmental impacts of their M&R plans. By identifying environmental hotspots and supporting the comparison of alternative strategies, LCA equips decision-makers with valuable insights to make more informed choices (Harvey et al., 2016). Note that information alone does not necessarily result in environmental gains, and relying solely on this function may entail addressing savings in other areas of the PM process to achieve improved sustainability outcomes.

Building on its information functions, LCA can further support decision-making by assessing the environmental performance of different M&R plan scenarios, accounting for factors that road agencies can manage, such as the scheduling and types of M&R treatments applied (Harvey et al., 2016). However, optimizing environmental performance at the network level requires a comprehensive approach that goes beyond LCA alone. Achieving sustainability gains and effectively mitigating the environmental impacts of M&R plans involves a complex and multidimensional process that extends beyond the evaluation of environmental performance. Table 61 compiles key capabilities ascribed to

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[38] PINs are indicators includes in the SLAs to evaluate the performance of RWS activities. However, challenges arise when translating strategic policy goals into operational PINs, as they may not fully capture the nuances of the objectives or reflect the direct impact of RWS actions. These aspects can hinder the direct relationship between the PIN score and RWS activities, affecting the accuracy of performance assessment (Ministerie van Infrastructuur & Milieu & Ministerie van Financiën, 2016). To address this, it is necessary to ensure close alignment between the defined PINs and the intended policy goals, enabling improved accountability and a more precise evaluation of the services provided by RWS.

LCA frameworks aimed to assist network planning in early PM, along with a brief description on how the EPMF performs in relation to these capabilities.

Table 61. Capabilities of the EPMF in assisting network-level planning.

Requirement	Source	EPMF	Description
Is standardized	(Liu et al., 2022)	Yes / No	The design of the framework is based upon official Dutch LCA guidelines. However, it is not completely aligned with the RWS LCA approaches and resources.
Includes nation-specific inventory data	(Harvey et al., 2014; Liljenström et al., 2020; Liu et al., 2022)	Yes / No	Empirical quantities are retrieved from the NL-PCR and available Dutch pavement LCA studies. The background system is modelled with ecoinvent 3.3 (which is fairly similar to the NMD database) but can be operationalized with the NMD provided its applicability and availability.
Has flexibility to update inventory data	(Liljenström et al., 2020)	Yes	The inventory data that feeds the model can be updated in response to new information and PM needs.
Has flexibility to replace default inventory data by project-specific data	(Liljenström et al., 2020)	Yes	The default inventory data provided within this report can be replaced as the PM process progresses and more information becomes available.
Incorporates uncertainty analysis and manages its results	(Liljenström et al., 2020; Liu et al., 2022) / This study	Yes / No	The framework includes an uncertainty analysis methodology that can evaluate the influence of uncertainty due to different parameters and methodological choices in the results. While the framework provides guidance for communicating uncertainty. It does not offer a well-defined approach for outlining the implications of the provided information to inform decision-making, nor does it provide support in using or leveraging uncertainty information for decision-making purposes.
Identifies environmental hotspots and areas of improvement	(Harvey et al., 2014; Liljenström et al., 2020)	Yes / No	The framework can identify the processes with dominant contributions to the environmental impacts and uncertainties. Moreover, it can identify the process with the largest opportunities for environmental reductions based on their contribution to the uncertainty. It is important to note that this task, in principle, is limited to individual M&R measures, but can be adapted to the M&R plan scale.
Can link performance models with environmental impacts assessments	(Harvey et al., 2014; Liu et al., 2022)	Yes / No	The results of IRI and MPD models can be fed into the framework to evaluate the influence of PVI effects in the environmental impacts. However, this is a task that requires the executor to manually transfer the results from the performance models to the LCA model, if available. The RWS does not currently employ nor has developed official IRI, MPD, RR, and fuel consumption models that are required to model PVI effects. Though this project has delivered models and a standardized procedure to calculate PVI effects, they should be interpreted as a starting point and should be further revised and refined. Consequently, ICO does not systematically employ the performance models that are required to determine PVI effects, which makes a direct link to them virtually unfeasible at this stage.
Can present results relative to reference alternatives	(Harvey et al., 2014; Liljenström et al., 2020; Liu et al., 2022)	Yes/ No	The framework can compare different scenarios applied to individual M&R measures but has limited comparability capabilities between M&R measures. As a result, the framework does not offer clear guidelines on how to compare multiple M&R plan alternatives composed by a large collection of M&R measures in a comprehensive manner, let alone how to do it systematically. Furthermore, it does not provide clear direction on how to account for the effects of uncertainty beyond the measure scale, nor how to compare them against one another.

Requirement	Source	EPMF	Description
Targets multidimensional effectiveness optimization	(Harvey et al., 2014; Liu et al., 2022; Santos et al., 2019)	No	The framework is not designed as a DSS and cannot directly balance environmental impact against costs and technical performance. Its results, however, can be placed alongside other factors to complement decision-making.

While the EPMF already exhibits several of these capabilities, there are key aspects that require further development to assist network planning, particularly if the framework aims at a decision-support role. Arriving to sustainability-driven optimized network choices in real-world PM decision-making hinges upon effectively managing the trade-offs between multiple conflicting factors (Cao, 2020), namely environmental impacts, costs, and technical performance (Harvey et al., 2014; Liu et al., 2022; Santos et al., 2019). Dealing with trade-offs has long-been a priority when using LCA to support decision-making (Laurin et al., 2016). In the early PM context, this role requires that LCA is placed within a broader multidimensional DSS framework, with the capability to actively assess different M&R strategy alternatives against one another (Harvey et al., 2014; Liljenström et al., 2020; Liu et al., 2022) as well as including an explicit link to pavement performance models (Harvey et al., 2014; Liu et al., 2022).

To effectively integrate environmental performance as an optimization criterion in early PM and arrive to more sustainable choices, it is essential to incorporate the EPMF within a broader PMS framework, leveraging the information that it provides, including the uncertainty results. PMS archetypally encompass a range of tools and methods that assess and predict current and future pavement conditions, build and optimize M&R plans, and estimate their costs (Harvey et al., 2014; K. A. Zimmerman, 2011). By employing LCA for informative purposes, LCA-based frameworks like the EPMF complement the information provided by the PMS and fill the gap in knowledge regarding the environmental impacts of network plans in PM. Figure 39 depicts how LCA is used to inform network-level decision making. However, by integrating environmental performance into a broader PMS framework, the EPMF can shift from being primarily informative to actively supporting decision-making in pavement M&R planning, ensuring that sustainability savings are addressed early in PM.

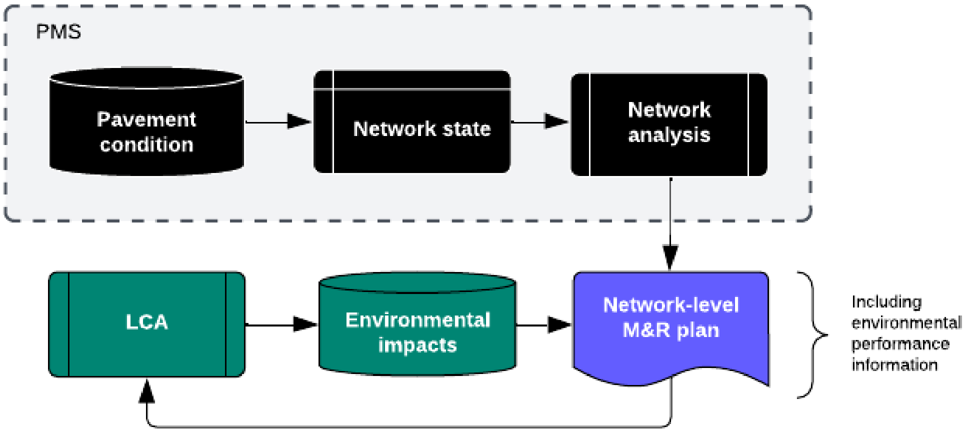

Figure 39. Application of environmental performance to inform network-level decision-making.

In the context of a PMS, LCA can either be integrated directly into the system or conducted externally and subsequently incorporated as policy within the PMS in order to meet network-level environmental goals and objectives (Harvey et al., 2014). In both cases, decision-making must weigh in the environmental impacts of different M&R plan scenarios, which are expected to vary across the network. This enables the optimization of M&R scheduling and treatment selection to minimize environmental impacts, which may include determining trigger values for different M&R actions and selecting measures that are suitable to meet the objectives (e.g., choosing specific overlay thicknesses and/or choosing between different M&R treatments) (Harvey et al., 2014). Figure 40 illustrates both LCA-PMS integration approaches.

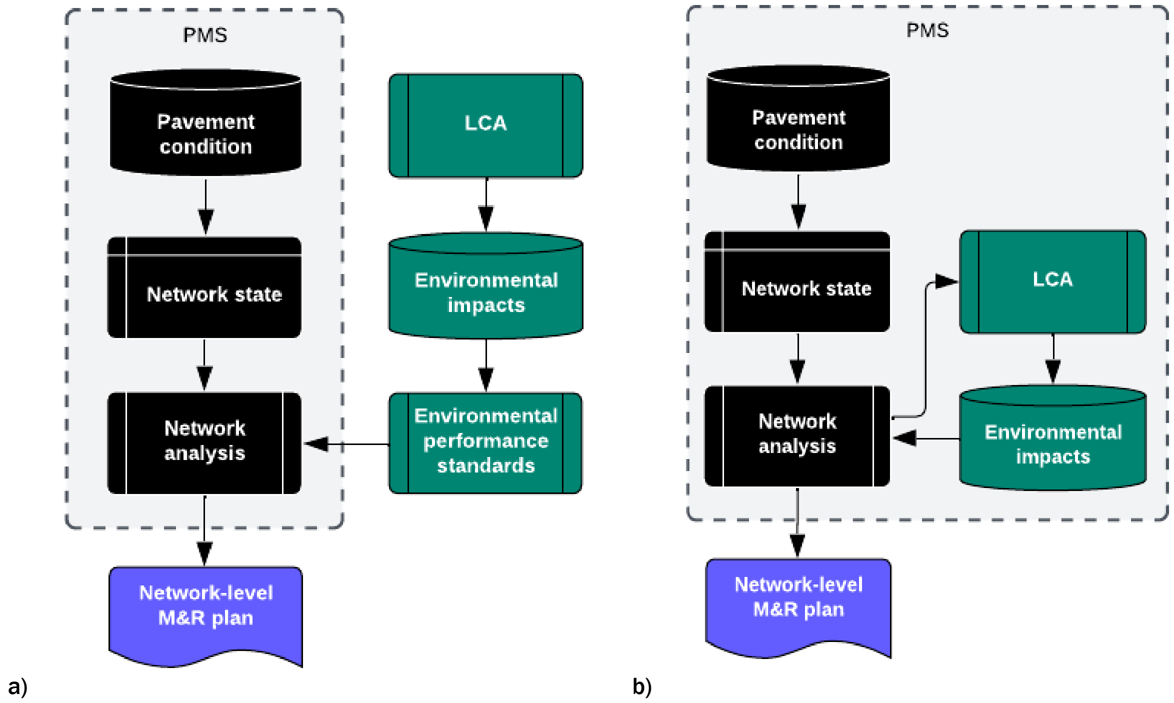

Figure 40. LCA to support network-level decision-making: a) conducted externally and incorporated as standards in the PMS, and b) conducted within the PMS.

When LCA is integrated within the PMS, it can provide decision-making support from within the system itself, allowing users to consider the environmental performance of different M&R options, including treatment decisions and scheduling options, straight from the PMS interface (Harvey et al., 2014). Considering multiple scenario outcomes is a well-established approach in decision-making that can be supported by LCA (Pryshlakivsky & Searcy, 2021a). For example, this approach can facilitate the evaluation of the environmental trade-offs between different design lives, where increased durability frequently implies lengthier M&R cycles. While this can lead to cost savings, less disruptions, and environmental savings in production and construction, these may come at the expense of increased RR and reduced fuel economy (Harvey et al., 2014; Liu et al., 2022; T. Wang et al., 2012). Optimizing pavement M&R plans requires a balance between the environmental impacts caused by pavements requiring treatment and the impacts generated by the treatments themselves (Harvey et al., 2014).

Another example involves the relative performance of alternative treatments (Harvey et al., 2016). Different M&R options can be compared based on their environmental impacts, selecting treatments that not only meet technical requirements but also maximize environmental savings. In this example, it is important to bear in mind that while maintenance measures have the potential to reduce the life cycle impacts associated with production and construction and delay rehabilitation interventions, their influence on RR has not been properly addressed. Consequently, it is difficult to accurately position their net environmental benefits against those of rehabilitation when considering PVI. Although maintenance measures may offer clear opportunities for environmental improvements, the comprehensive assessment of their effects on RR and overall environmental performance is necessary for a meaningful comparison with rehabilitation measures (see Chapter 7.4.1.1).

Taking a different approach, LCA can also be conducted externally to establish environmental performance standards further integrated into the PMS as decision trees (Harvey et al., 2016). LCA can be instrumental to defining thresholds that should not be crossed in decision-making (Pryshlakivsky & Searcy, 2021b). This format offers a structured approach for selecting and scheduling M&R treatments based on different benchmarks and criteria that include environmental performance aspects. Adding environmental standards to the PMS ensures that environmental considerations are systematically addressed in early PM decisions, including the choice of M&R design lives, treatments, and trigger levels based on pavement condition (Harvey et al., 2016).

Regardless of the role it serves, it is crucial to consider how uncertainty results can align with the intended purpose. Understanding how to interpret and leverage these uncertainties is essential. By comprehending the uncertainties associated with LCA results, pavement managers can gain a clearer understanding of the reliability and limitations of the provided information. This empowers them to make more informed and reliable decisions, considering the inherent uncertainties in the assessment process.

8.3.1 UNPACKING THE ROLE ESSENTIALS

The further development and implementation requirements of the EPMF are contingent upon the specific function it aims to fulfill in early PM and the approaches that it can adopt to achieve so. Two EPMF roles were determined in the previous section, each fulfilling a different purpose: (1) to inform network-planning, or (2) to support decision-making in the context of a PMS either (a) externally or (b) internally. The EPMF demonstrates well-developed information capabilities, making it relatively more adept to fulfill an informative role. However, there are still a few points that need to be improved, particularly regarding the challenges of comparability, compatibility, integration, and uncertainty results management. Moreover, a formal strategy should be established to effectively integrate the full scope of M&R plans within the framework, viewing the plans as a collection of measures whose cumulative impacts equal the plan's environmental burden. Conversely, supporting decision-making, while highly desirable, is considerably more challenging to accomplish. To achieve this role, the EPMF must be positioned within the broader context of a PMS, where it can actively support sustainable PM at the network level and influence the development of M&R plans. Figure 41 provides a detailed representation of the LCA structure placement to support M&R treatment selection and scheduling under a PMS framework.

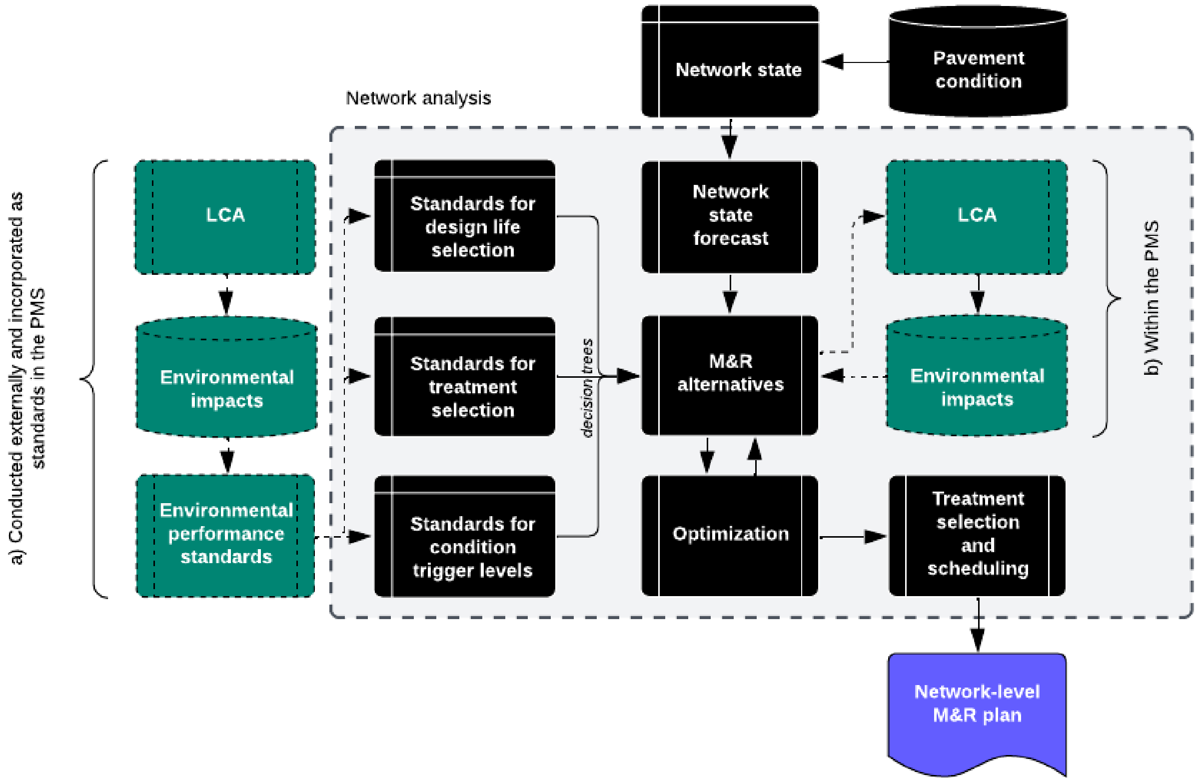

Figure 41. Zoom into LCA to support network-level decision-making a) conducted externally and incorporated as standards in the PMS, and b) conducted within the PMS.

Optimizing M&R plans by integrating LCA with PMS involves addressing a complex problem with multiple pavement performance conditions, costs, and environmental criteria and objectives, which may also need to be balanced within budget constraints and other relevant considerations (Harvey et al., 2014). Historically, the standards for scheduling and selecting M&R treatment options are usually based on the evaluation of pavement conditions (pavement deterioration models, M&R trigger values, etc.), short-term and long-term M&R effectiveness indicators (e.g., performance jumps, deterioration rate reduction, treatment service life, average pavement condition, agency and user costs, etc.) and cost-effectiveness optimizations (Harvey et al., 2014; Liu et al., 2022). Integrating environmental considerations into the mix entails the development and subsequent implementation of relevant pavement deterioration models, M&R trigger values and effectiveness indicators, and sustainability optimization techniques.

Pavement managers should prioritize the environmental hotspots that can be influenced during the early planning stage (Liljenström et al., 2020). When integrating environmental criteria into network-level planning, the parameters that drive PVI effects are arguably the most important aspect to examine and consider. LCA-based frameworks tailored to the early PM needs, like the EPMF, should incorporate PVI effects into the analysis irrespective of the role that they perform. Incorporating the analysis of fuel consumption during the use stage is a critical factor in improving environmental performance in network-level planning (Harvey et al., 2014). Addressing environmental savings through improved fuel economy often yields more significant outcomes compared to other stages in the pavement life cycle. This finding is supported by the case study results presented in Chapter 6.1, as well as by several studies in the field (Harvey et al., 2014; Liu et al., 2022; Santos et al., 2022; van Haaster et al., 2015; T. Wang et al., 2012). However, PVI effects and management are currently not addressed at any point of the PM process.

To accurately assess the impacts of PVI, the EPMF relies on pavement performance and fuel consumption models. Performance models are required to capture roughness, macrotexture, and, if available, deflection features (Harvey et al., 2014; Liu et al., 2022). These models should provide the information required to estimate RR and additional fuel consumption. In this context, prediction models should provide IRI and MPD progression estimates throughout the analysis period until the next M&R cycle following the last intervention, which can later be used as input for the use phase analysis (Harvey et al., 2016). In order to support these models within the PMS, access to additional inputs such as traffic data (volume, vehicle type distribution, speeds, and flows) and climate data (temperatures and rainfall) may be necessary (Hammarström et al., 2012; Harvey et al., 2014, 2016; Liu et al., 2022; Van Dam et al., 2015), as exemplified in the calculation of PVI effects for this report (Chapter 5.2.2.6.2).

Traffic plays a crucial role in assessing the environmental impacts of pavements from two perspectives (Harvey et al., 2014). Firstly, it influences the rate of pavement deterioration, particularly in relation to HDV traffic, which in turn influences the frequency of the treatments. Secondly, the effects of RR on fuel economy are different for (1) different vehicle types, and (2) different traffic intensities. Therefore, when sourcing traffic data for LCA, it is essential to capture these two aspects and ensure that they are accurately represented.

To effectively determine the appropriate M&R treatment decisions for different pavement conditions, employing trigger values alongside performance prediction models is required. Ideally, performance models will be directly linked to the LCA assessment and dictate what and when treatments will be triggered (Harvey et al., 2016). From an environmental standpoint, the optimization of M&R plans scheduling revolves around identifying optimal triggers based on the IRI and MPD values that result in the greatest net environmental savings, often expressed in GHG emissions or global warming units (Chong & Wang, 2017; Harvey et al., 2014; Liu et al., 2022). Studies have shown that delaying M&R when IRI triggers have been surpassed significantly decreases the environmental savings potential (T. Wang et al., 2014). However, it is important to note that determining these triggers is a complex process influenced by a range of factors, which require careful consideration.

Traffic intensity has a serious influence on the definition of optimal RR-related triggers. In general, the higher the traffic intensity, the lower the triggering IRI value must be to maximize environmental savings (Harvey et al., 2014, 2016; Liu et al., 2022; T. Wang et al., 2014). For example, a review conducted by Liu et al., (2022) noted that Chong & Wang, (2017) found that the PVI-induced emissions attributed to pavements enduring heavy traffic were more sensitive to IRI trigger value changes. They recommended IRI thresholds of 1.96 m/km for heavy and medium traffic, and 2.36 m/km for light traffic. The review authors also noticed that, in a subsequent study, Chong et al., (2018) balanced both life-cycle costs and environmental impacts criteria, resulting in optimal IRI trigger values of 2.3 to 2.65 m/km, 2 to 2.5 m/km, and 2.1 to 2.55 m/km for heavy, medium, and light traffic levels, respectively. The considerable difference between the results of both studies highlights the need to account for the specific interests sought by road agencies in determining optimal condition-based M&R thresholds.

It is important to keep in mind that, in certain instances, road segments characterized by relatively low traffic intensities can exhibit negative net environmental savings over a given analysis period across all IRI triggering values, suggesting that the emissions incurred during the M&R production and construction phases are not worth the roughness benefits ensued (Harvey et al., 2014). As previously mentioned, when PVI is factored into the equation, optimizing pavement M&R plans must balance the environmental impacts caused by pavements requiring treatment and the impacts generated by implementing the treatments (Harvey et al., 2014).

Balancing environmental impacts against costs and pavement performance requirements requires the adoption of sustainability optimization techniques. In the literature, various PM DSS frameworks that incorporate LCA alongside other dimensions have been proposed. Some authors have resort to multi-criteria decision analysis (MCDA) methods to find a balance between the multiple dimensions (Abu Dabous et al., 2020; Marcelino et al., 2019; Santos et al., 2019; Torres-Machí et al., 2015; Zheng et al., 2018, 2019), whereas others have employed multi-objective optimization (MOO) techniques to address the same challenge (Chen et al., 2022; Santos et al., 2018; Torres-Machí et al., 2017; Yu, Meng, et al., 2018; Zhang et al., 2010). The results obtained by employing these methodologies are influenced by the relative weight given to the various dimensions and the objectives sought by the PMS, which are dependent on what the road agency considers to be most important (Harvey et al., 2014).

While addressing the impact of PVI is key, the decision-making process in early PM should consider environmental performance throughout all stages, including production, construction, and EOL. Although the significance of these stages in attaining environmental savings may intensify during later phases of the PM process, particularly at the project level, it is essential to integrate sustainability considerations from the outset to maximize environmental improvements. At the network level, it is important to consider the environmental impacts associated with these phases when determining design lives. The justification for shorter lives and more frequent rehabilitation cycles, for instance, relies on the potential net environmental savings resulting from RR improvements. Additionally, the selection between either maintenance or rehabilitation treatment alternatives can also be influenced by the environmental impacts of these choices, provided that the PVI effects ramifications of each alternative are carefully compared.

8.4 THE EPMF TODAY: MATURITY EVALUATION AND PROGRESSION

The evaluation of the EPMF using the Technology Readiness Level (TRL) scale (Mankins, 2009) provides valuable insights into its maturity and implementation, which vary in function of the role that it aims to fulfil. The TRL scale consists of nine levels that represent different stages of technology development. The lower TRL levels (1-3) denote the early stages, including basic research and feasibility studies where concepts are formulated, and initial proofs of concept are established. TRL levels 4-5 indicate the intermediate stages, where prototypes are developed and tested. TRL 6-7 represent advanced stages, where prototypes are further demonstrated and validated in relevant environments, showcasing operational effectiveness. TRL 8-9 indicate the final stages, where the technology has proven to work in its application context and full implementation is achieved.

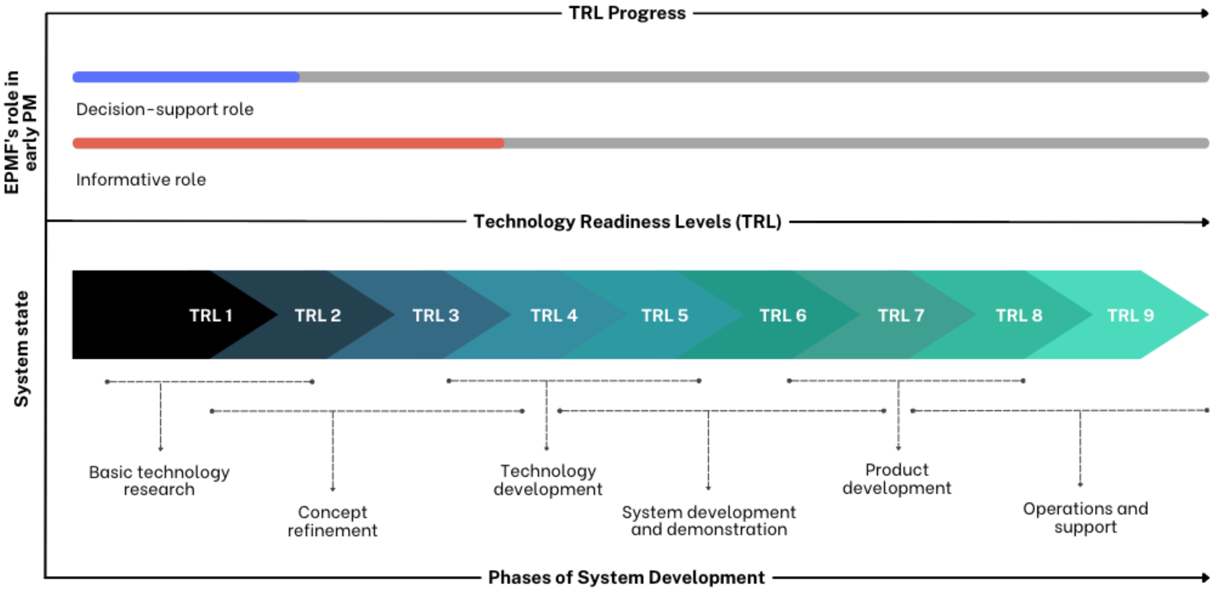

Figure 42. Maturity level of the EPMF based on the TRL – system development scale and its assigned role in early PM operations.

The EPMF is a systematic approach or methodology rather than a specific technology but can still be situated within the TRL scale. By applying the TRL scale to assess the state of development of the EPMF, its position within the stages of system development can be understood (Olechowski et al., 2015; Sauser et al., 2006). The premise of this study is that the EPMF takes after the early TRL stages of an LCA-based tool or technology to inform or support decision-making in early PM, representing the fundamental phases of technology research and concept refinement within system development. By understanding the position of the EPMF therein, necessary steps to progress towards implementation and drive further development can be determined. Figure 42 illustrates the EPMF position on the TRL scale based on the role that it aims to fulfill.

As mentioned previously, the maturity of the EPMF varies depending on its role. In the context of an information role, the EPMF demonstrates greater maturity, situated at the concept refinement phase of system development (TRL 3-4). A proof of concept and early prototype have been successfully delivered in the form of the digital tools created to conduct the case study, proving its feasibility, validating its design, and outlining key points for further refinement. However, as a DSS, the EPMF is less mature (TRL 1-2). While its informative functions have been well-established at higher TRL levels, specific decision-support capabilities are still in the early stages of exploration and require further research and development.

The EPMF currently exists as a standalone informative instrument, lacking integration with PMS and overlooking the technical and economic aspects of M&R strategies. While the EPMF has the virtual capacity to estimate the environmental performance of any given M&R plan, it currently falls short in forthwith steering decision-making or straight enabling more sustainable large-scale network-level planning. Exploring the decision-support role of the EPMF raises important questions about the framework design requirements. How does employing LCA to support network-level decision-making impact the design of the EPMF? This EngD project focused on designing a methodological framework for information purposes in early PM rather than as a fully-fledged DSS. Exploring how the framework design requirements change when integrated with other systems is necessary to assign the framework a DSS role. This chapter adds to the basic technology research, delivering an initial conceptual framework of the EPMF as a DSS in early PM within the scope of a comprehensive PMS. It provides a platform for ongoing exploration and refinement, aiming to growth its value for decision-making support.

8.4.1 KEY DEVELOPMENT ACTIONS

Shifting to higher TRL levels involves refining and integrating the EPMF with existing and/or new systems (depending on its role), as well as conducting extensive validation and verification to ensure its robustness and applicability in ICO, as well as in further stages of PM.

Given what each EPMF function requires and how mature the EPMF is in each, several key development actions per role were determined (Table 62). The first role, hereby referred to as *Role 1*, captures the informative functions of the EPM, while the second one encapsulates the decision-support functions and is further split into *Roles 2.a* and *2.b* depending on whether the EPMF is operationalized externally and incorporated as standards in the PMS or directly within the PMS, respectively.

Table 62. Key actions to advance the EPMF and each of its potential early PM roles.

Key development actions	Role 1: Info.	Role 2.a: DSS	Role 2.b: DSS
1. Address compatibility and integration issues.	X	X	X
2. Address comparability issues.	X	X	X
3. Refine uncertainty framework and manage uncertainty results.	X	X	X
4. Scope to the M&R plan scale.	X	X	X
5. Development and ink to pavement performance models.	X	X	X
6. Development of environmental performance standards, including design live, treatment, pavement performance and scheduling trigger values.	NA	X	X
7. Development, revising, refining, and incorporation of optimization strategies and techniques.	NA	X	X
8. EPMF – PMS interface: operationalization and implementation of EPMF within PMS.	NA	NA	X
9. PMS assembly: update/ replace iVON2.	NA	X	X
Notes: 1 = informative; 2 = decision-support where a) indicates that the EPMF is operationalized externally and incorporated as standards in the PMS, and b) that the EPMF is operationalized directly within the PMS; NA = not applicable.			

Compatibility and integration within the broader organization are important aspects that need to be addressed in development and implementation. The participants of the focus group corroborated the feasibility of implementing the EPMF within ICO, while acknowledging the heightened complexities involved in its application across other PM stages mostly credited to fragmentation and incompatibility issues (see Chapter 0). Ideally, the output of the EPMF should be of interest for all the actors involved in the PM cycle, and its use should eventually extend to the rest of the stages. Neglecting to address this assimilation risks rendering the environmental impact results obtained during network-planning irrelevant or undermining their worth in the rest of the process, particularly when the EPMF undertakes an informative role.

Table 63 illustrates an example of how environmental information obtained using the EPMF can be integrated throughout the PM process, based on an external report exploring the potential implementation of MKI calculations beyond procurement (Mentink, 2021). The table showcases the potential flow of environmental information, demonstrating how it can be incorporated and updated at different stages of PM as well as the actors involved in each step of the process. It's important to mention that within this context, environmental performances include uncertainty ranges. As underscored by the interview findings, uncertainty ranges could play a pivotal role in establishing robust MKI ranges and conducting coherence checks during procurement and execution. Additionally, they provide a mechanism for contractors to ensure safeguards during monitoring. While these advantages may not be directly related to the roles discussed in this chapter, they undeniably hold the potential to enhance PM and serve as enablers for the extensive adoption of the EPMF.

Table 63. PM environmental performance information flows example. Based on Mentink et al., (2020).

Stage	Description	Participants
Network-level planning: *reference framework*	An environmental impact database for M&R measures is developed, constantly upgraded, and made available in the OBR to facilitate environmental performance calculations. Alongside, environmental performance standards based on policy and regulations (e.g., SLAs and/or PINs for sustainability and transition paths) are established and continuously revised. A reference environmental performance for network-planning is calculated based on the MJPV and the environmental impact database.	RWS: GPO (W&G and ICO), sustainability advisors, SLA manager.
Programming	The MJPV and IHPs are adjusted by the regions based on different desirability and feasibility aspects. The network-level reference environmental performance is updated and adjusted to reflect these changes and the reference environmental performance for programming is delivered accordingly.	RWS: ICO, regions, network link team.
Procurement and execution	The programming is divided into POFS, where KES are incorporated if necessary. The reference environmental performance for projects is defined thereafter. The required M&R services are brought to the market, including the reference environmental performance for projects that is required, and a contract is awarded to the contractor with the best bid under a MEAT format. The environmental performance of the winning bid serves as the definitive expected environmental performance. The contractor performs the works under the supervision of the RWS and the expected environmental performance is checked against the actual environmental performance.	RWS: regions, IPM team, PPO; Contractors.
Monitoring	MKI values (and their reductions) are continuously monitored throughout the PM cycle and documented for the generation of future SLAs and PINs hat will set future environmental performance standards.	RWS: PPO, GPO (W&G).

Notes: The outputs produced by applying the EPMF are underlined.

Key development action points that were identified when unpacking the role requirements of the EPMF, irrespective of the role that it performs are 1) addressing comparability issues, 2) managing and leveraging the uncertainty results, 3) encompassing the entire scope of the M&R plan, and 4) developing and linking pavement performance models. The last point is of special interest for the decision-support role. The advancement of the EPMF to higher TRL levels for this role aims to enable the optimization of network-level plans adhering to sustainability principles, aiming to maximize environmental benefits while still meeting technical and cost criteria. To achieve this, it is crucial to develop accurate RR and extra fuel consumption models, as well as to establish robust pavement performance data collection structures to enable the calculations. Improving environmental performance at the network-level cannot be effectively achieved without these integral components. Furthermore, effectively managing uncertainty results is key, as they can significantly influence the interpretation of information and subsequent decision-making. Improving the uncertainty framework itself is also important given its current complexity, high computational demands, and other limitations (see Chapter 7.4.4), especially when the EPMF seeks organization-wide integration and implementation.

Building upon the previous considerations, the progression of the EPMF's maturity within decision-support roles introduces additional challenges. Firstly, extensive research efforts are needed to define environmental standards that can be incorporated into a PMS, both at the network-level and strategic-level (Liu et al., 2022). Owing to its framework-setting role (Rijkswaterstaat, 2022b), the RWS must establish sustainability objectives aligned with the national roads' sustainability agenda, providing a basis for determining the environmental standards for PMS training. Secondly, while the EPMF focuses on environmental aspects, it overlooks cost and technical goals typically sought by a PMS. Balancing these objectives and ensuring compatibility among different PMS subsystems requires dedicated research and development projects. As a result, integrating the EPMF into a PMS, both externally and internally, entails significant system development and customization efforts, potentially requiring alterations to existing software or even the development of new systems, particularly in the case of the latter integration case. This presents challenges in terms of technical implementation and compatibility with ICO's PM infrastructure and software, i.e., IVON2.

To facilitate the integration of the EPMF into a PMS, the use of the Integration Readiness Level (IRL) scale is recommended (Eder et al., 2017; Sauser et al., 2006, 2010). The IRL scale can review the integration level of the EPMF with other PMS components which are needed to optimize M&R plans and provide guidance on improvement strategies. The information delivered in this chapter begins the schematization of the potential interfaces between the EPMF and a PMS, starting the integration tasks attributed to IRL 1.

8.5 THE EPMF TOMORROW: TRANSITION PATHWAY SCENARIOS

Taking a strategic and forward-thinking approach is paramount to steering the direction of the EPMF, ensuring its meaningful contribution to sustainability, and preventing it from becoming an empty endeavor. The justification for investing time and resources into the development and implementation of the EPMF within ICO and the RWS requires a clear understanding of how its operation can extend to the broader PM context. As ICO is situated at the start of the PM operations chain, ensuring that the environmental performance information that they generate is actionable is fundamental to achieving environmental gains, whether through the EPMF's decision-support role within their operations or its informative role in later stages of the process. Figure 43 illustrates these visions. However, transitioning from theory to practice presents unique challenges, and deciding the future of the EPMF involves considerations beyond what key actions are needed to enhance its maturity.

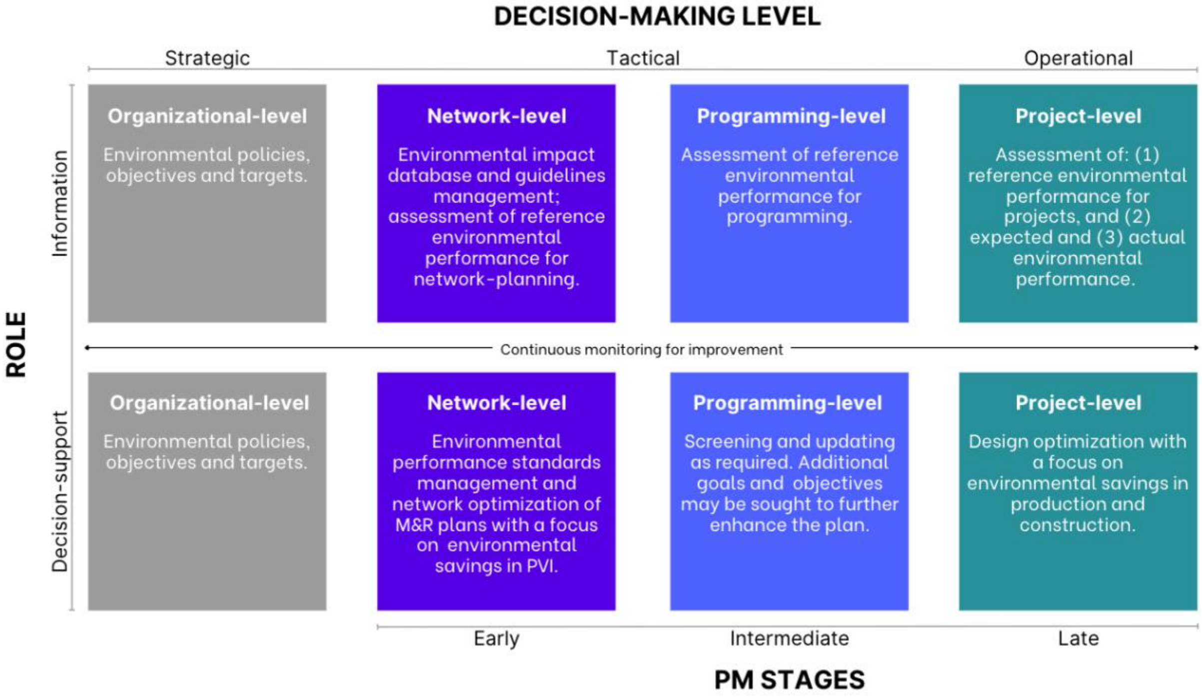

Figure 43. Vision of the EPMF's functions per role and across decision-making levels and PM Stages.

Deciding how to move forward with the EPMF calls for a closer look to the socio-technical picture of PM under these perspectives, where various multi-level interactions shape the course of action and are reciprocally influenced by it. Socio-technical pathway scenarios provide valuable insights into the multi-level interplay between individual innovations and policies, regime transformations, and their mutual influence, facilitating the exploration of possible futures (Geels, 2005, 2007; Geels & Schot, 2007; Hofman & Elzen, 2010; Kern, 2012; Verbong & Geels, 2010). Three distinct socio-technical transition pathway scenarios were developed for the EPMF and are described in Table 65. They capture the potential evolution of the EPMF in different roles based on different conceptualizations of the ongoing sustainability transition. These scenarios cover reconfiguration and transformation paths, pronouncing the development and implementation of the EPMF in informative and decision-support roles, respectively. Following the methodological steps to develop socio-technical scenarios defined by

Hofman & Elzen, (2010), and considering how the maturity of a given innovation influences transition pathways (Turnheim & Nykvist, 2019), the pathway scenarios hereby delivered offer qualitative storylines that outline possible futures for the EPMF.

The depicted scenarios have diverse implications, not only in terms of their approach to environmental savings but also in the system transformations that they require for each future. Scenario 1 represents a less disruptive option that aligns well with the current socio-technical regime conditions. It requires fewer research and development efforts and can be implemented in the medium-term. However, the realization of this scenario is heavily dependent on other actors in the PM domain to improve environmental performance and may have a lower potential for environmental savings since it does not provide a conclusive approach to address the effects of PVI. On the other hand, scenarios 2.a and 2.b present higher potential for environmental savings with less dependency on other PM actors, but at the cost of greater disruption. They require regime transformations, increased research and development efforts, and longer time horizons. Table 64 provides an overview of the main differences between these pathways.

Table 64. Key differences between transition pathway scenarios.

Key implications	Scenario 1	Scenario 2. a	Scenario 2. b
Environmental savings potential	Low / moderate	High	High
Environmental savings location	Strategic decision-making and late PM	Early PM	Early PM
PVI effects treatment	Inconclusive	Environmental standards	Environmental standards and optimization
Dependency of other PM actors	High	Moderate	Moderate
Disruption level	Low / moderate	High	High
Research and development efforts	Low / moderate	High	High
Time horizon	Medium- / long term	Long-term	Long-term

Based on the analysis results, scenario 1 appears to be the most feasible pathway for the EPMF's implementation by ICO and the RWS, despite scenarios 2.a and 2.b offering greater potential for environmental savings. In scenario 1, the EPMF serves an informative role and the primary responsibility for achieving environmental savings lies with the production system and industry structure. This strategy aligns well with the identified expansion opportunities for LCA within the PM cycle as recognized by the RWS (Mentink, 2021). However, this pathway may not fully achieve the desired maximum incremental sustainability sought by the RWS (Rijkswaterstaat, 2020), as it presents challenges in addressing PVI improvements.

The current procurement and collaboration methods in the Netherlands predominantly involve contractors only in the design and build phases of infrastructure projects (Lenferink et al., 2013). This confines their possibilities to apply life cycle optimizations only to the production and construction life cycle stages of pavements and restricts their strategic plan-making options, which limit their ability to achieve PVI-related savings. New links and collaboration models between government-led plan-making and private sector-led implementation are necessary to integrate PVI considerations under this regime.

Table 65. EPMF's transition pathways scenarios definition according to its designated function.

Role and socio-technical pathway scenario description	Storyline
1. Informative role Application of LCA to inform network-level decision-making. The environmental performance of network plans is calculated after the plans have been developed to inform network-level decision-making and subsequent PM stages. *Reconfiguration scenario* The EPMF targets ICO's local sustainability challenge. The RWS regime rules and architecture remain unchanged. Consequently, the framework is not explicitly positioned within the sustainable road pavements transition pathway. The EPMF is developed and implemented by ICO as an add-on to inform early PM. In principle, it does not modify ICO's infrastructure or protocols, but rather complements them. However, it is in principle not compatible with the RWS' LCA infrastructure. DuboCalc. Over time, the EPMF triggers incremental adjustments in the basic architecture of PM in the RWS. The RWS' existing LCA architecture gradually starts to converge with that of the EPMF. However, its use for network optimization is not strategically pursued.	Driven by economic, functional, and organizational reasons, the strategy currently outlined in the sustainable road pavements roadmap remains intact. Achieving environmental savings at in early PM by leveraging the LCA of M&R plans, including PVI effects, is not placed within the sustainability transition priorities. Environmental savings are addressed at the production system and industry structure level, and the innovations currently outlined in the transition roadmap amass most of the attention and resources. ICO, however, commits to the local deployment of the EPMF for information purposes. To further enhance the maturity of the EPMF following the TRL framework, ICO drafts and commissions new research and development projects. This includes addressing compatibility and comparability issues, refining the framework, and the development and link to pavement performance models. In the meanwhile, ICO starts exploring and using the current version of the EPMF for controlled applications and tests. Through an iterative cycle, a refined prototype embodying the EPMF is created and tested in ICO's operations, progressively reaching a nearly operational status. This includes strengthening its connection with the output of IVON2 and the subsequent incorporation of its results to the MJPV reporting. Alongside, the EPMF starts receiving moderate attention beyond ICO in the RWS. Once proven effective in delivering the environmental performance of M&R plans, the EPMF becomes an integral part of ICO's M&R network-planning practices. The environmental performance outcomes derived from the EPMF are properly integrated into the MJPV, ensuring accessibility across different stages of the PM process. This integration reinforces the recognition of the EPMF's role in communicating environmental performance throughout PM. To prevent the valuable output of the EPMF from being marginalized amidst the complexity of the PM process and maximize its potential, attention is directed towards its uptake in later PM stages. Efforts are made to embrace its widespread adoption and ensure its continuous application to uphold the value of environmental performance information in PM. Priority is given first to the integration and reception of the EPMF at the programming stage, building on the attention that it had received before. As a result, the EPMF guidelines and tools evolve to fit later PM stages and needs. Simultaneously, the possibility of extending the guiding principles of the EPMF to other infrastructure domains is discussed. In the broader operation, as the PM process progresses, the data input into the EPMF is managed and updated as needed by the management network (in line with the data resources), to reflect new information and changes to the M&R plans. This ensures that the environmental performance assessments remain up to date and aligned with new information. Furthermore, the regulations and policy aspects of PM become influenced by the EPMF, and its guiding principles are gradually incorporated into the PM standards of both ICO and the RWS. Over time, the methodology of the EPMF also begins to permeate the project-level and to influence prospective DuboCalc updates. The RWS launches projects and research initiatives to make this possible. This integration facilitates the inclusion of environmental considerations according to the standards of the EPMF in procurement, where their role and implications are investigated and asserted. Notable benefits brough by employing the EPMF in procurement corresponds to robust MKI ranges and coherence checks enabled by the provision of uncertainty ranges. Environmental gains at this stage remain sought by encouraging more sustainable design project proposals, with an emphasis on the production and construction life cycle phases

of pavement M&R. Contractual models in place prevent design project proposals from targeting environmental savings in PVI, rendering PVI calculations at this stage solely informative.

RWS, through the repeated use of the EPMF, gains valuable insights and leverages these lessons to refine and enhance their strategic standards (e.g., RBO, SLAs, OBR, etc.). This gradual and systematic process contributes to the ongoing improvement of environmental performance in PM. It is worth reiterating that the responsibility to pursuit environmental savings is mainly assigned to the production and industry structure, requiring contractors to deliver sustainability-enhanced project proposals as part of the green procurement strategy. The process of addressing environmental improvements in planning by focusing on improving PVI, still lacks clarity and a suitable implementation framework. The strategic decision-making level may opt to address this matter through broader policies, objectives, and targets. Additional efforts are required to make progress in this regard. As the RWS acknowledges that sustainability goals have not yet been achieved, the organization starts actively exploring possibilities and seeking potential solutions.

Additionally, over time, there is an ongoing reciprocal process of harmonization and improvement between the EPMF and the relevant Dutch LCA standards, extending beyond the confines of the RWS. The two approaches influence each other, iteratively refining their methodologies and aligning their objectives. This iterative process helps enhance both the EPMF and the Dutch LCA standards, ensuring their continued relevance and effectiveness, as well as promoting standardization in the sector. Furthermore, it provides the basis for a regulatory framework to include PVI in the environmental assessments of pavements.

2.a Decision-support role

Application of LCA to support network-level decision-making. Conducted externally and incorporated as standards in the PMS.

The EPMF is applied externally to define environmental standards for design life, treatment selection, and trigger levels based on pavement condition to further include in the PMS decision trees.

Transformation scenario

The existing sustainable road pavements transition pathway has come under scrutiny for its perceived limited approach to achieving environmental improvements. In response, the regime initiates a reorientation process, kickstarted by the introduction of the EPMF.

Developed and implemented by ICO, the EPMF becomes an integral part of the broader PMS employed in early PM. It delivers environmental standards that are implemented as decision trees and serves as a valuable source of information and decision-support.

In response to concerns regarding the limited scope of the sustainable road pavements roadmap raised by knowledge institutes, universities, and other actors of the sustainable road pavement socio-technical system, the RWS recognizes the need to address network-level savings and PVI effects to reach the sustainability goals of the sector. To avoid a potential regime destabilization, the sustainability transition strategy is revised and modified in collaboration with relevant stakeholders. Recognizing their role in developing network-level plans and the environmental opportunities therein provided, the RWS takes a proactive stance to optimize planning practices and expand the environmental savings responsibilities beyond the production and industry structure.

The updated transition strategy results in increased support in enhancing the maturity of the EPMF, both in its informative and decision-support roles. The RWS initiates parallel efforts to, on the one hand, improve the informative capabilities of the EPMF and, on the other hand, respond to its decision-support needs. Consequently, the RWS begins conducting and commissioning research and development projects to define and implement optimal environmental standards as decision trees based on the EPMF outcomes, as well as developing and incorporating multidimensional optimization approaches such as MCDA and MOO-based methods that can be employed in combination with the framework. Furthermore, emphasis is placed on developing, refining, and implementing PVI-related pavement performance and fuel consumption models.

As the individual components required to link the EPMF with PMS reach higher maturity levels on the TRL scale, the integration process begins, which requires additional research and development challenges on its own. The integration is based on the ‘LCA conducted externally and incorporated as environmental standards’ approach, which proved to be the most feasible and viable to transform the PM infrastructure of ICO and the RWS. The progress of this integration is monitored and evaluated in terms of the IRL scale, and the feasibility of incorporating the developed components into the existing IVON2 PMS is assessed. If necessary, the design of a whole new PMS software is considered as an alternative. ICO's PM infrastructure is transformed in any case. Moreover, the network-level planning PM protocols followed by ICO and the RWS evolve accordingly.

Simultaneously, other parties may develop similar approaches for other road authorities and government organizations, although the EPMF holds an advantage due to its relatively higher maturity stage and clearer vision for development and implementation, making it a better fit for the evolving regime of the RWS.

While the regime undergoes transformative changes, it still maintains its fundamental architecture, albeit employing optimized network-level planning methods that seek sustainability objectives and account for PVI effects, which transforms ICO's infrastructure and protocols.

The integration of the EPMF into the new PMS shows promising results in achieving network-level environmental savings, particularly regarding PVI effects, contributing significantly to the sustainability transition in the field. During this process, the EPMF informative role is parallelly leveraged by the actors involved in PM, following a pathway similar to that outlined in the informative scenario.

Overall, the EPMF becomes an integral part of PM, leading to cumulative adjustments and reorientations within the existing regime. While the basic regime architecture remains virtually unchanged, the approach to network-level planning is revamped to prioritize environmental benefits, account for PVI, and readily support the sustainability transition.

2. b Decision-support role

Application of LCA performance assessment to support network-level decision-making. Conducted within PMS.

The EPMF is applied within the PMS as part of the multidimensional optimization strategy employed for treatment selection and scheduling where different M&R plan scenarios are compared and assessed against multiple criteria.

Transformation scenario

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Developed and implemented by ICO, the EPMF becomes an integral part of the broader PMS employed in early PM, optimizing plans from within and serving as a valuable source of information and decision-support.

While the regime undergoes transformative changes, it stills maintains its fundamental architecture, albeit employing optimized network-level planning methods that seek sustainability objectives and account for PVI effects, which transforms ICO's infrastructure and protocols.

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As the individual components required to link the EPMF with PMS reach higher maturity levels on the TRL scale, the integration process begins, which requires a full research and development project of its own. The integration is based on the 'LCA conducted within the PMS' approach, which although challenging, proved to be the most desirable alternative to transform the early PM infrastructure of ICO and the RWS. The progress of this integration is monitored and evaluated in terms of the IRL scale, and the feasibility of incorporating the developed components into the existing IVON2 PMS is assessed. However, as the integration of the EPMF within the PMS is likely to be disruptive to the existing early PM infrastructure, it is likely that a new PMS architecture renders IVON2 obsolete and a whole new PMS software is developed. ICO's PM infrastructure is transformed in any case. Moreover, the network-level planning PM protocols followed by ICO and the RWS evolve accordingly.

Simultaneously, other parties may develop similar approaches for other road authorities and government organizations, although the EPMF holds an advantage due to its relatively higher maturity stage and clearer vision for development and implementation, making it a better fit for the evolving regime of the RWS.

The integration of the EPMF into the new PMS shows promising results in achieving network-level environmental savings, particularly regarding PVI effects, contributing significantly to the sustainability transition in the field. During this process, the EPMF informative role is parallelly leveraged by the actors involved in PM, following a pathway similar to that outlined in the informative scenario.

Overall, the EPMF becomes an integral part of PM, leading to cumulative adjustments and reorientations within the existing regime. While the basic regime architecture remains virtually unchanged, the approach to network-level planning is completely transformed to prioritize environmental benefits, account for PVI, and readily support the sustainability transition.

Increasing inclusiveness in terms of actors, scope, and time dimensions by turning to integrated and/or relational contracts (e.g., design-build-finance-maintain [DBFM] and public private partnerships [PPP], respectively) could facilitate a more sustainable asphalt pavement planning process and product (Lenferink et al., 2013), where contractors are given the platform to seek PVI improvements. If neither the current contractual and collaborative structures in PM evolve nor PVI is addressed at the network-level otherwise (e.g., through improved strategic standards), scenario 1 may not explicitly pursue PVI-related environmental improvements. The challenges to handle PVI and RR in PM could potentially explain why they are currently excluded from the scope of the current sustainable pavements transition roadmap.

The well-defined consideration of RR and PVI in scenarios 2.a and 2.b delivers a greater opportunity for maximizing environmental savings in pavement M&R. Nonetheless, their realization would require a transformation in the current regime and sustainability transition strategy. Despite the challenges associated with the existing regime conditions, these pathways may represent an inexorable route towards achieving improved sustainability in the sector. The escalating environmental concerns shaping the socio-technical landscape and the crucial role of PVI in addressing them mark the significance of these scenarios for the future. Note that contractors would also need to meet the decision-support considerations specified in these scenarios if they were to address PVI within an evolved PM collaboration structure. Building upon the existing body of literature, this report has further substantiated the importance of PVI and RR to reduce the life cycle environmental impacts of pavements. Moreover, this chapter has underlined the need of incorporating these factors into a comprehensive decision-making framework that fits PM needs using approaches like MCDA and MOO. To be well-prepared for the future, it is important to explore the evolution of potential pathways influenced by these factors.

Regardless of the role that it performs and its potential for environmental savings, the socio-technical pathway scenarios presented depict enterprises aimed at the introduction of the EPMF as an innovative approach to improve sustainability in the PM network. These interventions demand clear commitments to its development and implementation, such as supporting its ongoing piloting, improving its maturity, establishing proper knowledge creation infrastructures, and fostering relevant collaborations (Turnheim & Nykvist, 2019). With a deeper understanding of the potential development and implementation paths that the EPMF could follow, it is now possible to identify key factors that determine its success.

8.6 NAVIGATING THE PATH TO SUCCESS: KEY ATTENTION POINTS

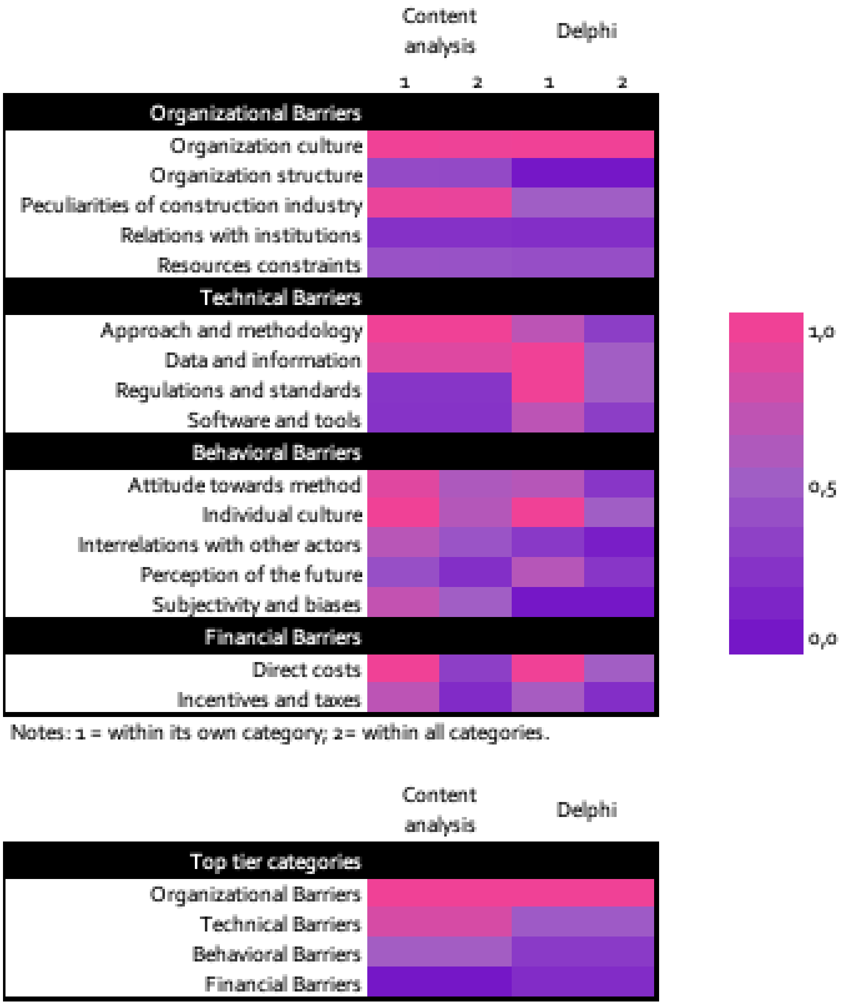
Fostering commitment to the sustained development and implementation of the EPMF by ICO and the RWS is essential to reach success. To gain a better understanding of commitment and effectively strengthen it, it is beneficial to examine it through three dimensions: affective, calculative, and normative (Y. K. Wang & Datta, 2009).

Affective commitment reflects the emotional attachment and identification that users feel towards the EPMF, driven by their perception of its performance and satisfaction. Calculative commitment involves the user's attachment to the EPMF including financial and non-financial costs such as the costs of development, training, investments, and opportunities. Normative commitment pertains to the sense of obligation and compliance that users feel towards the EPMF. Monitoring and nurturing these dimensions can strengthen the bond between ICO, the RWS, and the EPMF, reducing the likelihood of abandoning the development and implementation of the framework and consolidating its place in PM.

Enhanced commitment is instrumental in overcoming barriers to the adoption of the framework, and conversely, addressing barriers can contribute to strengthening commitment. D'Incognito et al., (2015) identified and ranked various behavioral, organizational, technical, and financial barriers to the adoption of LCA in the built environment context (Figure 44). Using content analysis and Delphi studies, the researchers determined that organizational and technical barriers are the most significant obstacles to LCA adoption in the sector. Specifically, organizational culture and the unique characteristics of the construction industry emerged as prominent examples of organizational barriers, while issues related to approach and methodology, as well as data and information, were identified as key technical barriers. Notably attitude towards the method and individual culture were found to be highly ranked behavioral barriers overall.

The socio-technical network analysis findings align with the research conducted by D'Incognito et al., (2015), which highlighted the significance of organizational and technical barriers in integrating the EPMF within the PM network. The barriers identified in previous sections include the need for organizational commitment, stakeholder endorsement, access to necessary data and information resources, and ample expertise, all of which influence commitment.

The successful development and implementation of the EPMF relies on effective stakeholder engagement and collaboration, which can be challenging in practice due to varying interests and priorities among different parties involved in PM. There needs to be a shift in the mindset and awareness within the organization, acknowledging the importance of environmental performance in PM. Stakeholders should be educated about the benefits of more sustainable PM practices and the role of the EPMF therein. Additionally, the EPMF requires sufficient expertise and information resources to properly conduct environmental impact assessments, which may be further limited by capacity and budget constraints (i.e., resource constraints and direct costs). Knowledge transfer through training programs, workshops, and sharing best practices can facilitate the adoption the EPMF in PM.



Notes: 1 = within its own category; 2= within all categories.

Figure 44. Barriers to the adoption of LCA: relative importance. Adapted from D'Incognito et al., (2015).

While action across all PM socio-technical domains is crucial to address these barriers and strengthen commitment, particular attention must be given to the role of the management network. Without a dedicated individual or entity taking ownership of the EPMF and assuming responsibility for its development, implementation, and management, the effectiveness of the framework may be compromised. This principle applies not only to the robust pathways depicted by the scenarios introduced in this chapter, but also to any other types of operationalization endeavors, including simpler implementations.

Responsibilities of the management network involve the integration of subsidiary processes, including budgeting, financial management, human resource management, and IT management, to support the long-term functioning of the system (Bennett, 2008), as well as regular updates of underlying models and data, e.g., annual review, periodic updates of methods, e.g., every two to three years, and conducting a major revision of the entire EPMF structure, e.g., every five to six years (Guinée et al., 2001). Table 66 provides a brief analysis of key influences of each scenario on all the socio-technical network elements of PM, as well as the associated barriers. This table compiles key attention points that should be addressed to successfully implement the pathways herein described and consolidate commitment to the EPMF's further development and implementation.

Table 66. Key implications and barriers of each scenario on the socio-technical network elements of PM.

Socio-technical elements of PM	Key barriers	Scenario 1	Scenarios 2.a and 2.b
Management network	*Organization culture**; organization structure; *peculiarities of construction industry*;* relations with institutions; *approach and methodology*;* software and tools.	Creation of a dedicated organizational unit that takes responsibility for its management and operation within the PM framework. This unit should be equipped with the necessary resources and staffed with well-qualified practitioners who actively contribute to its development and implementation. Moreover, it is crucial to integrate subsidiary processes such as budgeting, financial management, human resource management, and IT management to ensure the long-term functioning of the system.	ICO takes on the responsibility for the EPMF, ensuring its effective management and operation. To oversee the EPMF and its interfaces with other components of the PMS, a dedicated and well-qualified practitioner is appointed. Additionally, it is crucial to integrate subsidiary processes, including budgeting, financial management, human resource management, and IT management, to support the long-term functioning of the system.
Production system and industry structure	Relations with institutions; resource constraints; *data and information*;* software and tools; direct costs.	Access to data and information availability from the RWS and third parties is essential for operating the framework.	Access to data and information availability from the RWS and third parties, as well as increased collaboration with experts is essential for further developing and operating the framework.
User practices	*Organization culture*; organization structure; *approach and methodology*; attitude towards method*; individual culture**; interrelations with other actors; perception of the future; subjectivity and biases.	Demonstrating a clear and visible commitment from all actors involved in PM is essential for the successful implementation of the EPMF. This commitment encompasses the active participation and support of key stakeholders throughout the PM network. By employing the EPMF across the network, valuable environmental impact information can be generated.	The successful implementation of the EPMF's inclusive PMS relies on the demonstrable commitment of ICO. This commitment involves actively embracing the EPMF's principles and incorporating its results into their decision-making activities at the network level. It requires a change in practices within ICO to ensure the integration of the EPMF's findings and insights in

			their network planning and decision-making processes.
Symbolic meaning	*Organization culture*; peculiarities of the construction industry**; perception of the future.	The results of the EPMF coexist along cost and technical assessments criteria.	The EPMF is part of a broader multidimensional decision-support framework that strikes a balance between environmental, costs and technical criteria.
RWS and ICO infrastructure	Organization structure; *peculiarities of construction industry**; resource constraints; software and tools.	The EPMF is employed alongside IVON2. It may eventually seek future harmonization with DuboCalc.	The EPMS becomes part of IVON2 or an evolved PMS architecture.
Regulations and policies	*Organizational culture**; organizational structure; regulation and standards.	Establishment of explicit polices that direct the use and management of the EPMF, i.e., updated OBR directives.	Establishment of explicit polices that direct the use and management of the EPMF, i.e., updated OBR directives, SLAs, PINs, etc.

Notes: *key barriers.

Given the technical implications of scenarios 2.a and 2.b, where the EPMF is embedded within a larger PMS framework, it is important to look at the key factors that contribute to the success of a PMS, even though many of these have already been discussed and addressed. These factors are often categorized into three components: processes, people, and technology (Bennett, 2008).

For a PMS to be successful, it must have appropriate functionality that aligns with the organization's processes. This includes generating annual M&R network plans as well as establishing monitoring and evaluation mechanisms to track progress and ensure desired outcomes are achieved. In this context, this entails monitoring the environmental performance outcomes and their improvement. Furthermore, the institutionalization and support of the PMS are essential. This entails the establishment of a dedicated organizational unit with specific responsibility for the system, allocation of stable and sufficient budget for its operation, and implementation of continuous training mechanisms to enhance user proficiency, similar to the requirements of the EPMF alone. Lastly, the technology adopted for the PMS should be appropriate for the institution, considering its capabilities and resources. The functional requirements of the PMS should reflect the objectives of the RWS, integration with other PM systems should be ensured, and the establishment of hardware and software maintenance agreements should be prioritized. Additionally, a robust IT structure and budget must be in place to support the effective functioning of the PMS. This dimension should be carefully explored when deciding between the way in which the EPMF is employed to support decision-making in the PMS, or, in other words, when choosing between scenario 2.a and scenario 2.b. By addressing these key points, the successful integration of the EPMF within the broader PMS framework can be facilitated, ensuring its effectiveness and long-term functioning.

8.7 DEVELOPMENT AND IMPLEMENTATION CONCLUSION

To transition from a conventional approach to sustainable PM, it is fundamental to adopt a comprehensive strategy that encompasses various aspects. This includes fostering mindset changes, making necessary policy adjustments, actively engaging stakeholders, building capacity, and integrating approaches like the EPMF. The sustainability transition is an ongoing journey that requires gradual change and continuous improvement to align PM practices with environmental sustainability objectives. Applying the EPMF could play a significant role in this process.

The EPMF is specifically developed to assess the environmental performance of network-level plans in the initial stages of PM. While it currently has the technical capability to fulfill this purpose, the journey to fully leverage its outputs in driving the sustainability transition is still in progress. This chapter provides a comprehensive analysis of the potential development and implementation of the EPMF within ICO and the RWS, considering two key roles that it can fulfil in PM to support the transition: to inform or to support decision making. The study examines how can these functions be capitalized to achieve environmental gains in the context of PM and assesses its level of maturity in performing them. Furthermore, based on an analysis of the socio-technical context of sustainable road pavements and PM, three transition pathway scenarios were developed, each corresponding to a specific function of the EPMF. These scenarios facilitate the identification of key barriers and attention points that need to be considered to reach successful development and implementation.

It is worth noting that the scenarios presented in this chapter provide a glimpse into potential outcomes in the medium- and long-term, assuming the successful development and implementation of the EPMF along a defined trajectory, irrespective of their role and environmental savings potential. These scenarios explore various conditions that make the realization of a pathway more feasible, including system integration, infrastructure, societal acceptability, maturity, and political feasibility (Turnheim & Nykvist, 2019).

The information that this chapter provides serves as a valuable resource for ICO and the RWS to make informed decisions about the EPMF and shape the path forward. However, it is important to note that the scenarios provided should be viewed as explorations of the future rather than precise predictions. The actual development and implementation of the EPMF may encounter undisclosed challenges such as conflicting interests, delays, deviations, stalemates, or competition from alternative approaches. Therefore, the objective of this chapter is to present a comprehensive map of different actions that could lead to successful outcomes rather than a step-by-step plan, while highlighting and comparing the potential contributions of the EPMF and similar LCA-based frameworks to the sustainability transition in the sector. In doing so, it sheds light on the existing gaps in the current sustainability approach within the sector and calls for proactive measures to address them.

Building upon the findings of the case study, this chapter highlights the significance of considering PVI and the associated fuel consumption resulting from increased RR over time to enhance the environmental performance of network-level planning and maximize sustainability in the pavement sector. By integrating this factor into the decision-making process, pavement managers can determine optimal roughness levels for different sections of the network and strategically schedule maintenance and repair (M&R) activities. This approach aims to support the design of M&R schedules based on indicators such as IRI and MPD, which act as triggers for network-level decision-making, with the overarching goal of maximizing environmental sustainability. Achieving this vision, however, poses significant complexity and challenges, primarily due to the deliberate exclusion of these elements from the current sustainability strategy embraced by the regime.

This chapter features the inclusion of PVI and RR considerations in two of the three presented scenarios. However, it is important to note that the remaining scenario, which does not explicitly address PVI and RR, appears to be a more feasible option given the current regime conditions. Unfortunately, the current set of initiatives aimed at improving environmental performance in the sector does not encompass PVI and RR improvements. Nevertheless, by recognizing the potential benefits of incorporating PVI and RR in the sustainability pursuit, further exploration and evaluation of the feasibility of integrating these elements into network-level planning processes and the overall sustainability transition strategy are encouraged. Neglecting to do so may result in suboptimal environmental improvement outcomes and ineffective actions. For example, although the regime actively promotes the use of more durable asphalt surface mixtures to reduce the environmental impacts of production, construction, and EOL (Duurzame Infra, n.d.), the potential environmental impacts associated with increased RR over extended lifespans during the use phase must be considered to get an accurate picture of the net environmental savings that this initiative can offer. By considering the complete life cycle of pavement infrastructure, including the use phase impacts, the sector can plan interventions more effectively.

In conclusion, the vision of sustainable road pavements is dynamic and constantly evolving to accommodate future landscape needs and demands. Moving forward requires a willingness to learn, experiment, and adapt as necessary, ensuring that PM practices continually adapt to meet the evolving sustainability goals. It is imperative for the regime to proactively align with this dynamic vision, capitalizing on the strengths and insights gained from historical and current contexts. Recognizing that there is always room for improvement, the integration of approaches such as the EPMF becomes crucial in influencing progress and ensuring that sustainability remains a central in PM practices. By embracing continuous improvement and innovation, the regime can pave the way for a more sustainable and resilient future for road pavements infrastructure.

9 PROJECT CONCLUSION

Previous chapters have extensively delved into discussions, conclusions, limitations, and recommendations pertaining to the design and implementation of the EPMF. Reiterating all these aspects here would be redundant. Instead, this chapter marks the end of this report, offering conclusive insights into the overall project. It presents the most relevant elements and findings of this research.

This EngD project introduced the EPMF, an LCA-based methodological framework to evaluate the environmental impacts of pavement M&R interventions, while accounting for various types and sources of uncertainty. In principle, this framework was conceived as a supporting instrument in formulating network-level M&R plans for the main road network in the Netherlands. While initially tailored to the Dutch main road network, the EPMF exhibits adaptability to various contexts.

Throughout its development, the EPMF addressed three significant research gaps in pavement LCA literature: 1) the need for a framework adapted to the early stages of PM, characterized by limited information and high uncertainty, 2) the necessity to incorporate all life cycle phases, including the impacts of PVI, and 3) the integration of robust uncertainty analysis methodologies.

The EPMF's guidelines support the environmental assessment of different M&R measures, ranging from asphalt overlays and bituminous surface treatments to machine-based treatments to improve surface roughness. By disaggregating the impact of the measures into the pavement structure system elements and considering the particularities of each, comparison can be more straightforward and easily done. The influence of PVI during the use phase is incorporated via performance models and established fuel consumption models (Hammarström et al., 2012). The uncertainty assessment methodology combines stochastic sampling and scenario analysis techniques, yielding PDFs that describe environmental impact results. Additionally, three GSA methods—Sobol, PAWN, and Extra Trees—are employed to assess result sensitivity to input value variations.

Demonstrated through a case study involving a mill-and-fill DZOAB treatment on a road pavement segment within the Dutch main road network, the results emphasize that accounting for the use phase overshadows any other impact reductions occurring in other phases, even for modest PVI impact values. This underscores the significance of including the use phase in the analysis and control pavement condition during the analysis period to reduce extra fuel consumption. Furthermore, the sensitivity analysis revealed a dominating contribution of PVI to the uncertainty in the results. Further sensitivity analyses excluding the use phase underline the substantial impact of transportation processes on uncertainty. Identifying the parameters that introduce the most uncertainty to the results substantiates why should pavement managers should pay them more attention.

Among the methods employed, Extra Trees and PAWN emerged as particularly advantageous in executing sensitivity analyses. Notably, they operate significantly faster than Sobol while virtually maintaining the same level of accuracy. Moreover, PAWN holds an additional advantage as it accommodates non-normal distributions. Consequently, conducting GSA via Extra Trees and PAWN is recommended.

Arguably, one of the most notable findings of this study is the significant contribution of PVI to the environmental impacts of pavements, echoing a perspective that has been a topic of widespread discussion among the pavement community (Akbarian et al., 2012; Gregory et al., 2016; Harvey et al., 2014, 2016; Noshadravan et al., 2013; Santos et al., 2022).. This highlights the critical need for reliable RR and fuel consumption models to account for increased emissions and environmental burdens caused by pavement deterioration. Failure to include PVI effects in LCA models can lead to a significant underestimation of the environmental impacts. Moreover, not considering PVI may lead to believe that performing maintenance against rehabilitation will always result in net environmental savings (Faghih-Imani & Amador-Jimenez, 2013). However, acknowledging the broad spread of such impacts in the case study results underscores the challenge of accurately assessing PVI effects, hindering efforts to make it a standard part of pavement LCA. Recognizing the potential for PVI to significantly dominate the environmental impact results, both in the best cases and particularly so in the worst ones, should motivate further research to improve prediction models and advance the pavement community's understanding of this critical issue.

The outcomes of this project underscore the pressing need for transformative shifts in decision-making processes during the early PM stages, aiming to maximize environmental gains and support the sustainability transition in the pavement domain. In this context, the EPMF assumes a pivotal role. This research delineated two promising pathways through which Dutch PM can usher in this evolution, leveraging the capabilities of the EPMF: 1) informing decision-making and 2) supporting the mitigation of the environmental impacts of network M&R plans. The EPMF provides valuable environmental insights for informed decision-making, which can eventually lead to network choices that balance environmental impact, costs, and technical performance. Currently, it provides valuable information on the environmental performance and uncertainties of M&R plans, but it is not a DSS or an active component of a PMS. Recognizing the need for further development efforts is necessary to enable the systematic involvement of the EPMF in optimization strategies and decision-making.

It's important to acknowledge that while LCA frameworks, including the EPMF, serve as a mean to assess the environmental performance of products and systems, it should be integrated with other tools and approaches that encompass broader and long-term sustainability considerations. The EPMF effectively identifies potential environmental hotspots and facilitates comparisons among various pavement alternatives, yet it doesn't provide a holistic evaluation of overall sustainability. When conducting pavement LCA studies, it is important to consider not only environmental impacts but also social and economic aspects (Santos et al., 2019; Thomé et al., 2016; Zheng et al., 2018). Moreover, one must assess whether a project is sustainable overall (Bjørn et al., 2020), and how does it capture circular economy principles (Mantalovas et al., 2020; Thomé et al., 2016). For example, the EPMF can tell whether option A is has better environmental performance than option B and where the largest impacts lie, but it cannot say whether the option is sustainable overall or if it follows circularity principles. The option may not be sustainable overall if it relies on non-renewable resources, exceeds carrying capacity, has negative social or economic impacts, or does not meet other sustainability criteria (Ellsworth-Krebs et al., 2023), not to mention circularity performance. Helpful strategies are to look at the concept of planetary boundaries, which can be used to evaluate whether a project or a sector operates within the limits of the Earth's resources and ecosystems (Bjørn et al., 2020; Rockström et al., 2009), and leverage LCA results to evaluate circularity (Dieterle et al., 2018; Lei et al., 2021).

The EPMF proves to be a valuable LCA framework, aiding pavement managers in making more informed decisions and delivering promising avenues for environmental impacts' mitigation. However, it's crucial to keep the underlying data updated and further refine the approach as discussed in Chapter 8. Moreover, while it delivers valuable insights into the environmental performance of M&R, it is just one piece of the larger sustainability puzzle. In PM decisions, considering multiple dimensions of sustainability and circular economy aspects, besides particular aspects relevant to PM, is fundamental, and the EPMF should evolve to encompass these views.

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A LIFE CYCLE ASSESSMENT FRAMEWORK FOR PAVEMENT MANAGEMENT CONSIDERING UNCERTAINTIES

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ABSTRACT

Life cycle assessment (LCA) is a methodology widely endorsed by the pavement community and increasingly adopted by transportation agencies worldwide to account for the environmental impacts of pavements throughout their entire life cycle. LCA studies in this context are prone to the effects of uncertainties due to (1) the long analysis periods that stretch across numerous maintenance and rehabilitation (M&R) cycles, (2) the need of different types and sources of data and additional models and (3) multiple methodological decisions to be made by the analyst. Nevertheless, LCA studies are often done deterministically and omit important phases and phenomena from the systems boundaries, thereby reducing the reliability and representativity of the results. To overcome this challenge and to foster the integration of LCA models with existing pavement management systems, this paper presents the development and application of a LCA framework that evaluates the environmental performance of pavement M&R treatments. Further, it incorporates the effects of pavement-vehicle interaction into the analysis and accounts for multiple types of uncertainties, namely those associated with the value of parameters, methodological choices and data quality. Probability distributions and value scenarios are used to characterize the uncertainties which are propagated into the results using Latin hypercube sampling and scenario analysis. A sensitivity analysis using tree-ensemble methods is adopted to unveil the most influential parameters on the variance of the outputs. The outcomes of this research work aim to advance the applicability of LCA in the context of pavement management, and to improve the understanding of the effects of uncertainties in the outcomes of the analysis.

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INTRODUCTION

Road pavements are long-lived infrastructures that undergo periodic maintenance and rehabilitation (M&R) treatments over their lifetime. The application of such treatments ensures that pavement condition remains above desirable levels, but it also results in significant cumulative environmental impacts due to the vast consumption of natural resources and energy it entails. In light of the rising environmental awareness, assessing the environmental impacts of road pavements is an important step towards the achievement of sustainability goals.

Life cycle assessment (LCA) is an approach that evaluates the environmental impacts of road pavements over the course of their service life that has gained significant recognition in the field of pavement management (PM) and has become instrumental in the context of sustainability transition (Miliutenko et al., 2014; Rangelov et al., 2020; Santero et al., 2011; Santos et al., 2015). However, the validity of LCA in this setting is often called into question, as most pavement LCA studies tend to exclude important phases from the system boundaries of the analysis, particularly the use phase (Xu et al., 2019), and ignore the effects of uncertainty on the results.

LCA offers the option to calculate the impacts of pavement materials production, construction, use, M&R, and end-of-life (EOL) (Santero et al., 2011). Conventionally, the focus of the assessment has been placed in the production, construction and EOL phases (Xu et al., 2019). However, as the environmental impacts of the use phase may represent a large share of total life cycle impacts (Harvey et al., 2016; Santos et al., 2022), recent LCA studies have begun to account for the effects of pavement-vehicle interaction (PVI), a use phase mechanism, in their assessments (Akbarian et al., 2012; Gregory et al., 2016; Noshadravan et al., 2013; Santos et al., 2022). PVI is the relationship between pavement characteristics and vehicle fuel efficiency, determined by pavement rolling resistance (RR). As RR increases, so do the fuel consumption and the emissions generated by the vehicles moving across the road (Bryce et al., 2014; Van Dam et al., 2015). Although in a comprehensive analysis it is essential to take into account every phase of the pavements' life cycle to ensure representativity and accuracy, the absence of the use phase is not the only omission often found in multiple pavement LCA studies.

Uncertainty is unavoidable in LCA studies, and despite the fact that it directly affects the reliability of the results, conventional LCA analyses often consider single input values. The need for the consideration of uncertainties in LCA has been recognized in the past (Huijbregts, 1998; Santero et al., 2011), but limited attention has been given to developing and including uncertainty analysis approaches in LCA studies (Lo Piano and Benini, 2022), let alone in the pavement domain.

The first step of a un uncertainty analysis in LCA consists of identifying and selecting the main types and sources of uncertainty (Igos et al., 2019). This includes distinguishing between parameter and scenario uncertainty. Parameter uncertainty is primarily caused by inaccuracies in input data used to model processes and flows caused by data quality and variability. LCA studies in the pavement domain place attention on several specific sources of parameter uncertainty related to the different pavement life cycle phases (Azarijafari et al., 2018; Gregory et al., 2016; Noshadravan et al., 2013; Santos et al., 2022), including PVI and the models used to predict the pavement condition over time (Gregory et al., 2016; Noshadravan et al., 2013; Santos et al., 2022; Ziyadi et al., 2017). Among other sources, scenario uncertainty arises from methodological and normative choices made during the goal and scope definition, such as LCA software and LCI database selection (Santos et al., 2017), system boundary choices (Gregory et al., 2016), allocation methods (Azarijafari et al., 2018), etc.

After identifying sources and types of uncertainty, the next step is to characterize them. Characterization can be done qualitatively or quantitatively. In qualitative characterizations, it is common practice to estimate data quality levels and to construct alternative scenarios based on different methodological choices (Igos et al., 2019). The pedigree matrix approach implemented in the ecoinvent database (Weidema et al., 2013) has been employed in the pavement LCA field to account for the uncertainty due to data quality, rendering its further quantitative characterization possible (Azarijafari et al., 2018; Gregory et al., 2016; Noshadravan et al., 2013). Quantitatively, uncertainties can be characterized by defining minimum and maximum parameter values and/or probability density functions (PDFs) (Igos et al., 2019). Data variability can be represented with PDFs when the sample size is large (Yu et al., 2018), or by minimum and maximum values for smaller sample sizes (Gregory et al., 2016). When only single values are available, predetermined uncertainty values retrieved from the ecoinvent database can be used (Azarijafari et al., 2018; Gregory et al., 2016; Noshadravan et al., 2013). In turn, scenarios can be represented by discrete choices with equal likelihood or with alternative value scenarios (e.g., minimum and maximum values) (Azarijafari et al., 2018; Gregory et al., 2016).

Once uncertainties have been characterized, they are propagated to the results. Two common methods used in pavement LCA literature are Monte Carlo sampling (MCS) and scenario analysis (Azarijafari et al., 2018; Gregory et al., 2016; Noshadravan et al., 2013; Santos et al., 2022; Yu et al., 2018). MCS is a commonly used method to propagate parameter uncertainties (Igos et al., 2019). However, it requires large sample sizes and can be computationally expensive. To reduce the computational time, Latin hypercube sampling (LHS) can be used. It is an efficient modification of MCS that divides the input distribution into equal intervals from which a sample point is selected randomly (Groen et al., 2014; Igos et al., 2019). It guarantees that all intervals are sampled equally, and that no area is over- or under-sampled. Therefore, it is particularly useful for contexts where the sample size must be kept as small as possible. Scenario analysis entails the single or simultaneous variation of parameters, methodological choices and model formulations to analyze uncertainties in LCA (Igos et al., 2019). Sampling and scenario analysis can be used together to combine parameter and scenario uncertainties (Azarijafari et al., 2018; Gregory et al., 2016).

Moreover, a comprehensive uncertainty analysis in LCA should include a sensitivity analysis to investigate how changes in parameters and methodological choices affect the results (Harvey et al., 2016) and to identify which elements have the largest contributions to the overall uncertainty (Igos et al., 2019). In the pavement field, one-at-a-time analyses (Godoi Bizarro et al., 2020) and Spearman's rank correlation coefficients (Gregory et al., 2016) have been used to identify the most influential parameters and scenarios. In other fields, the calculations of Sobol indices (Igos et al., 2019; Jaxa-Rozen et al., 2021a), a well-known global sensitivity analysis (GSA) technique, has been adopted to quantify the relationship and importance of each input in the variance of the LCA outputs. However, this method comes at a high computational cost. In turn, Extra Trees is a computational efficient method that can handle large number of parameters and produce reliable results at smaller sample sizes, while offering results comparable to those of Sobol indices (Jaxa-Rozen and Kwakkel, 2018). In LCA, Extra Trees has been used as a preliminary screening step to identify the most influential parameters on the uncertainty (Jaxa-Rozen et al., 2021a), but to the authors' best knowledge it has never been applied in the pavement LCA field.

In view of the considerations and limitations mentioned above, this study aims to further expand the development and applicability of LCA in the context of sustainable pavement management by creating a framework tailored to road pavement M&R that accounts for the effects of PVI and includes a comprehensive uncertainty analysis methodology.

METHODS

LCA Framework

The proposed LCA framework described in this paper focuses on the LCA of individual pavement M&R cycles that involve the application of asphalt overlays, although it can be expanded to include any other type of M&R treatments. LCA studies in the context of M&R often cover long analysis periods spanning multiple M&R cycles. In the current setting the analysis period is constrained to the time between the application of a treatment and the subsequent need for a new one. In addition to the analysis period, the definition of the functional unit considers the characteristics of the pavement system being treated, including its structure (surface, binder, and/or base layers and subgrade), geometrical and functional characteristics, materials, and the traffic it is expected to carry (Harvey et al., 2016).

Moreover, the LCA framework is consistent with Dutch reference documents, specifically the asphalt product category rules (NL-PCR) (Van der Kruk et al., 2022) and the Determination Method (Nationale Milieudatabase, 2020). The system boundaries for the analysis encompass all relevant life cycle processes and flows, including the production (material extraction, acquisition, transportation, and processing into asphalt mixtures), construction (on-site paving activities and equipment use), use (processes that impact the environment during the service life, with an emphasis on PVI) and end-of-life (EOL) phases (i.e. removal, recycling and transportation of waste materials) as outlined by Santero et al., (2011).

Uncertainty Analysis

The uncertainty analysis starts with the identification of the different foreground-related uncertain parameters and methodological choices that potentially can influence the environmental impact calculations. Although accounting for uncertainty related to the background is to some extent feasible and would result in a more robust analysis, its actual realization would imply an extreme increase of the number of uncertain parameters and the level of complexity the analysis.

Data variability can be represented with PDFs derived from empirical data when available, or with the predefined values provided by the ecoinvent method in the absence of empirical data (Weidema et al., 2013). These values are then aggregated with data quality uncertainty according to the criteria established by the ecoinvent method, with data quality being described using log-normal distributions. The procedure provided by Muller et al., (2016) is adopted to facilitate the numerical integration with data quality uncertainty values when data variability is represented using distributions other than log-normal. Scenarios are developed based on different value options, such as different machinery production rates, recycled asphalt pavement (RAP) content in the composition of the mixture, and the type of bitumen added.

In the proposed LCA framework the propagation of uncertainties to the results involves the application of a combination of LHS and scenario analysis. LHS is employed to reduce computational time in the evaluation of parameter uncertainty. Scenario analysis, in turn, is used to evaluate the effect of changing scenarios. According to Jaxa-Rozen et al., (2021), 12,000 simulations are sufficient for the LHS analysis when the sensitivity analysis method is adequate for a relatively small number of samples. As such, the Extra Trees method is adopted to identify the most influential parameters in the uncertainty of the outcomes for different scenarios following the configuration recommended by Jaxa-Rozen and Kwakkel, (2018). It is important to note that LHS should be performed for each scenario considered in the analysis, allowing for its subsequent sensitivity analysis. Figure 1 summarizes the uncertainty methodology proposed in the framework.

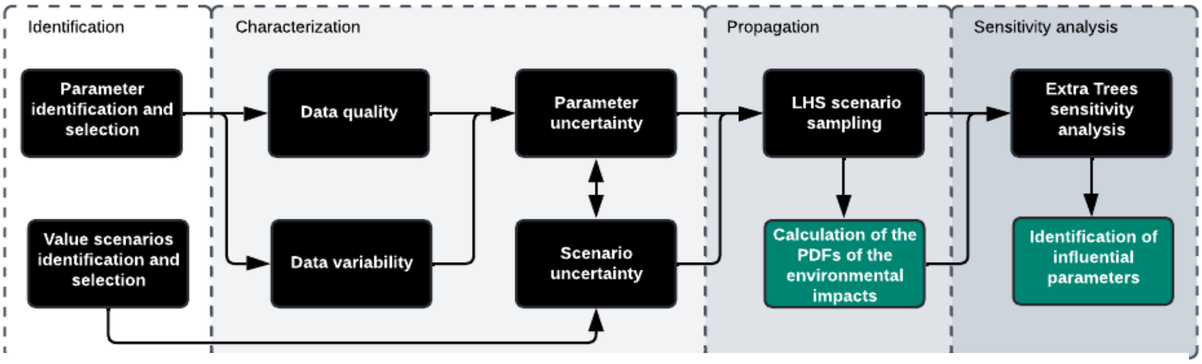


Figure 1. Uncertainty analysis methodology. Black boxes represent the application steps of the methodology, whereas the green ones depict the handling of the outcomes of the methodology.

CASE STUDY

The applicability of the proposed framework is illustrated by using the case study of a mill-and-fill M&R treatment for the main road pavement network in the Netherlands. The chosen treatment, selected from a collection of over 75 potential hot mix asphalt overlay options, involves the application of a 50mm-thick layer of Durable ZOAB (DZOAB), which is a porous asphalt mixture with enhanced durability commonly used in the Netherlands.

The functional unit for the analysis is defined as a straight and plan 1km-long carriageway road pavement segment section with 3 lanes, each 3.5km-wide. Traffic data, including average daily intensity values for passenger cars, heavy duty trucks (HDV), and HDV + trailers, were sourced from the INWEVA geographical information system and datasets (Rijkswaterstaat, 2022c) and are presented in Table 1. The traffic growth rate, set at 1.9%, was determined based on information from the National Statistics Office of the Netherlands (CBS, 2022a). The analysis period, corresponding to the average lifespan of a DZOAB surface, is 14 years.

Table 1. Traffic intensity in number of vehicles: statistics.

Vehicle type	Mean	Std	Min	Max
Passenger car	26064	17513	2276	101325
HDV	1744	1035	219	7292
HDV + trailer	2061	1477	140	8872

The system boundaries were adapted from the NL-PCR to align them with the context of M&R (Figure 2), with the exception of leaching, which was excluded from the use phase due to the absence of primary data (Van der Kruk et al., 2022). A construction rate of 1000 ton/ day was used in the analysis. Additionally, the environmental benefits of recycling RAP into new pavement materials outside the system boundaries were not considered as RAP enters the system free-of-burden in mixtures with RAP content. Input data for each life cycle phase, except PVI, were obtained from the NL-PCR and the Ecoinvent 3.3 database.

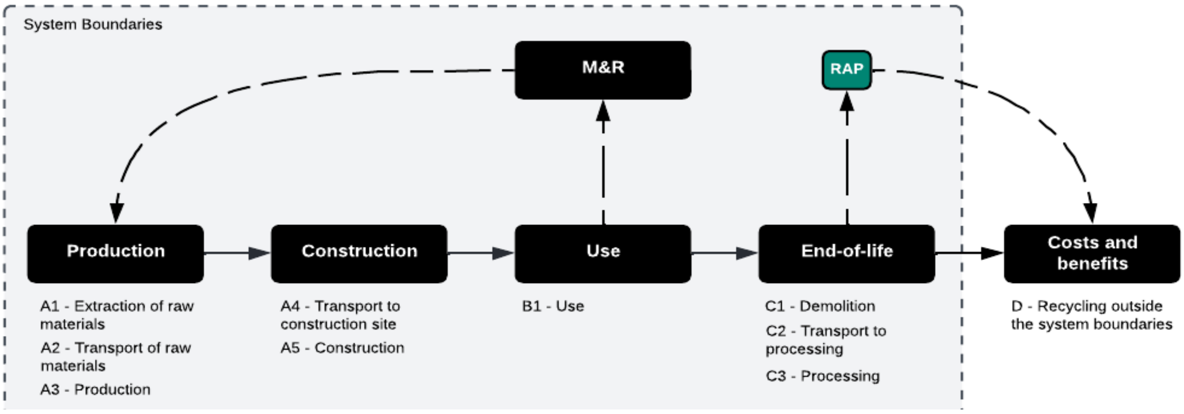


Figure 2. System boundaries of the case study.

The environmental impacts of PVI were calculated using the MIRIAM model (Hammarström et al., 2012). Moreover, linear models were developed for predicting the evolution of roughness and macrotexture over time, respectively represented by the International Roughness Index (IRI) and Mean Profile Depth (MPD), using real IRI and MPD measurements of the Dutch main road network provided by the Dutch Ministry of Infrastructure 'Rijkswaterstaat' (RWS). The values of the parameters of the performance models using pavement age as predictor are presented in Table 2. The results are assumed to follow a normal distribution with a mean corresponding to the predicted IRI and MPD values and a standard deviation (std) equivalent to the mean absolute error (MAE) of the model. Vehicle speeds were determined based on Dutch speed limits (Rijksoverheid, 2022) and were assumed to follow a normal distribution with a mean corresponding to the speed limits and a coefficient of variation of 0.1. For facilitating the calculation and to match the size of the traffic intensity sample of the Dutch road pavement network, approximately 4000 MCS runs were completed to estimate the total additional fuel consumption due to RR over the analysis period. The results follow a normal distribution, and the values of the parameters are presented Table 3. The environmental impacts were then calculated and incorporated into the LCA model using the method described by Santos et al. (2022), which uses the fuel efficiency and environmental impacts of transportation services (excluding the upstream impacts attributed to infrastructure) to model PVI effects.

Table 2. IRI and MPD linear pavement performance models parameters and statistics.

Pavement performance model	Year 0	Annual increase	MAE
IRI (m/km)	0.9993	0.0296	0.0325
MPD (mm)	1.1063	0.0209	0.1207

Table 3. Total extra fuel consumption due to RR in the analysis period (l/km).

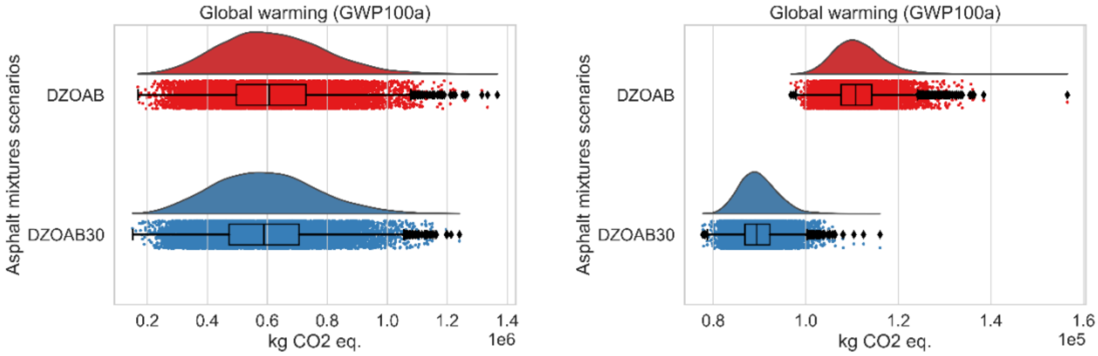
Vehicle type	Mean	Std
Passenger car	68967.84	46675.05
HDV	17729.00	10516.89
HDV + trailer	58536.78	41941.30

The uncertainty analysis was conducted using two scenarios for RAP content: (1) a mixture with 0% RAP and (2) a mixture with 30% RAP. The NL-PCR was used to determine the input values for mixture composition and energy expenditure for asphalt mixtures production, as well as diesel consumption for construction and removal processes, based on the amount of RAP in the mixture (Van der Kruk et al., 2022). All foreground input value parameters assigned to each scenario, including materials, transport, additional vehicle fuel consumption, and energy consumption for production, construction and EOL were considered in the analysis. Data quality uncertainty was calculated using the ecoinvent method (Weidema et al., 2013), as well as the variability of the parameters, with the exception of PVI, whose variability values were computed in the earlier step.

Each scenario was sampled 12,000 times with LHS, and environmental impacts of each sample were calculated using the OpenLCA software with a Python interface adapted from the one developed by Jaxa-Rozen et al. (2021b). To identify the most uncertain parameters, an ExtraTrees regression was applied using the scikit-learn Python library (Pedregosa et al., 2012). Finally, given that the environmental impacts of the use phase are expected to be predominant and highly uncertain, two additional scenarios in which one excluded the effects of PVI in module B (use phase) were considered to provide more meaningful insights on the influence of the several parameters on the uncertainty of the outcomes.

RESULTS AND DISCUSSION

The environmental impact results for the scenarios including and excluding the use phase are illustrated with the global warming impact category and are presented in Figure 3(a) and (b), respectively. From the analysis of the Figures, it can be seen the use of RAP allows the reduction of the environmental impacts, although this result is almost imperceptible when the use phase is considered. This is due to the overwhelming contribution of the environmental impacts associated with PVI, which outweigh the influence of the remaining phases.



a) b)

Figure 3. Environmental impact for scenarios (a) including PVI effects and (b) excluding PVI effects.

The results of the sensitivity analysis indicate that in scenarios that include the use phase, fuel consumption has the greatest influence on the uncertainty of the outcomes. This can be attributed to the large variability and predominant contribution of extra fuel consumption to the environmental impacts. In contrast, the contribution of other parameters in the scenarios thereof is relatively similar and mostly below the order of 1%. In scenarios that exclude the use phase, there is greater variation in the contributions of different parameters to uncertainty. Notably, transport has a significant effect on uncertainty, particularly the transportation of raw materials via transoceanic ships in module A1, and freight transport to and from the construction site in modules A4 and C2. This can likely be credited to the large uncertainty values assigned to transport exchanges by the ecoinvent method. When taking a closer look at individual life cycle phases, activities related to EOL in module C1, encompassing milling, sweeping and cleaning, and the consumption of natural gas for mixture heating in module A3, are Figure 3. Environmental impact for scenarios (a) including PVI effects and (b) excluding PVI effects. 970 the major contributors to total uncertainty after transport. Finally, when examining the contribution of raw asphalt materials processes in module A1 to total uncertainty, bitumen and large size aggregates present the greatest contributions from this phase.

CONCLUSION AND FUTURE RESEARCH WORK

In this study, an LCA framework is proposed for evaluating the environmental impacts of M&R treatments under uncertainty. The key features of this framework include the consideration of PVI in the analysis, the incorporation of parameter and scenario uncertainties in the assessment, and the application of a tree-based ensemble method for sensitivity analysis to determine the most influential parameters in the uncertainty of the outcomes.

The environmental impact results of the case study indicate that when the use phase is considered, the reduction of impacts occurring in other phases becomes imperceptible, even when PVI impact values are relatively low. This substantiates the importance of including the use phase in the analysis and ensuring that the pavement remain in good condition during the analysis period to reduce extra fuel consumption due to increased RR.

The sensitivity analysis conducted in this study revealed that in scenarios that include the use phase, the contribution of PVI to the uncertainty in the results is overwhelming. In order to gain a deeper understanding of the influence of the various parameters on the uncertainty, further sensitivity analyses were conducted using scenarios that exclude the use phase. The results showed that transportation processes have a significant impact on the uncertainty of the outcomes.

In conclusion, the outcomes of this research work helped to advance the applicability of LCA in the context of pavement M&R, and to improve the understanding of the effects of uncertainties on the outcomes. Further, it offers the possibility of identifying areas with the highest potential for environmental performance improvements by determining the extent to which impacts can be reduced.

Additional research work in this domain will be performed by incorporating other M&R measures beyond asphalt overlays. Additionally, the incorporation of advanced GSA techniques, such as variance-based and distribution-based methods (e.g., Sobol and PAWN), as well as the development of empirical uncertainty factors to account for process variability will be pursued.

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DISSECTING UNCERTAINTY IN LIFE CYCLE ASSESSMENT STUDIES FOR PAVEMENT MANAGEMENT – A STUDY OF TREE ENSEMBLE METHODS, DISTRIBUTION-BASED AND VARIANCE-BASED GLOBAL SENSITIVITY ANALYSIS

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Uncertainty analysis is an important component of the life cycle assessment (LCA) of pavements, as it allows practitioners to understand the impact of multiple sources of uncertainty on the results. LCA is an approach for evaluating the environmental impacts of road pavements over the course of their service life that has achieved widespread acceptance in the field of pavement management (PM). However, LCA studies in the PM context are subject to the effects of multiple sources of uncertainty, such as the quality and variability of the input parameters, as well as the methodological choices made by the practitioner. A comprehensive uncertainty analysis will help practitioners establish a range of possible LCA outcomes, make more informed decisions, and improve the robustness and reliability of the LCA results.

Multiple methods exist for incorporating uncertainty analysis in LCA, ranging from qualitative assessments to comprehensive quantitative analyses that include sensitivity analysis. A complete uncertainty analysis will not only seek to characterize and propagate uncertainties to the results but will also include a sensitivity analysis. A sensitivity analysis will investigate how changes in the input parameters influence uncertainty and identify its greatest contributors. This information can be used to identify the key sources of uncertainty in the LCA, prioritize which aspects should be addressed, and focus efforts on improving data, refining the model, or modifying methodological choices in order to reduce the overall uncertainty in the LCA results.

The importance of considering uncertainty in the life cycle assessment (LCA) of pavements is acknowledged within the PM community. However, it is common for LCA studies of pavements to be performed without taking into account the effects of uncertainty. There are limited studies available in which uncertainty analysis is integrated into pavement LCA studies. This study seeks to address this knowledge gap.

We compare the performance of three sensitivity analysis techniques that have been employed in the LCA of geothermal heating networks- Extra Trees regression, Sobol, and PAWN - in the context of PM using the example of the maintenance and rehabilitation of the main road network in the Netherlands as a case study. Extra Trees is a machine learning algorithm that models the relationship between input parameters and the results of an analysis by using a set of decision trees. The algorithm can determine the significance of input variables by using the Mean Decrease Impurity metric, where a variable is considered important when it is associated with a large decrease in impurity. Sobol is a well-established global sensitivity analysis (GSA) technique that uses variance to identify the most influential input variables on the system output by quantifying their relative contribution to the variance of the output. PAWN, on the other hand, is a distribution-based GSA method that evaluates the importance of inputs in the analysis by assessing changes in the output distribution rather than variance. While Sobol is widely used, it requires high computational resources and may not perform well when the output distribution is highly skewed. In contrast, Extra Trees is a more efficient alternative that offers similar results to Sobol, while PAWN is better suited for non-normally distributed LCA outputs and has a lower computational cost. The performance of each method is compared centered on their sensitivity findings and the identification of the most influential parameters on the uncertainty in the LCA outcomes. Based on the results, conclusions are drawn regarding the usefulness and applicability of each method in the field of PM.

Conducting uncertainty analysis can be time consuming and resource intensive, and not all LCA practitioners may choose to include this step in their studies. This study aims to bridge LCA and uncertainty analysis to advance the applicability and reliability of LCA in the context of PM and improve the understanding of uncertainty in the results.