BSc Thesis Civil Engineering
Department of Engineering Technology

# Developing a tool for integrated assessment of asphalt maintenance measures

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Final version
February 7, 2025

NTP

UNIVERSITY OF TWENTE.

Roelofs

# Preface

In front of you lies the final version of my BSc thesis report presenting a large-scale asphalt maintenance approach. This assignment completes my bachelor's degree in civil engineering at the University of Twente.

First of all, I would like to thank NTP for providing this interesting and practically oriented assignment on which I could work. I would also like to thank Roelofs and the municipality of Enschede-Losser, who played a role in this. I have really enjoyed working on this project in the office of NTP with my colleagues, as well as working on other locations where colleagues from Roelofs and the municipalities were also present. I have learned a lot from the lectures given by the companies and their new construction team.

During the thesis, many people have supported me, for which I am very grateful. To start, I would like to thank Pim Mulder, my external supervisor at NTP, for the support and feedback during the assignment. It was always possible to ask questions or to discuss different topics. This allowed me to quickly continue with what I was working on. Additionally, I would like to thank Kasper Wind, my second external supervisor at Roelofs, who provided me with important data for the project. Both my external supervisors have created a very pleasant working environment for me. A special gratitude is owed to my personal supervisor Andreas Hartmann from the University of Twente for guiding me through the thesis assignment and providing valuable feedback. This helped me a lot to create a complete and useful final product for attaining my bachelor's degree.

Lastly, I would like to thank my family and friends for their support helping me achieve this result.

Steven Menkveld

*Enschede, February 7*

# Summary

In the civil engineering field, the designing and construction of roads is important to maintain efficient and safe transportation networks. Roads play a major role in moving vehicles from their origin to their destination. Not only the construction of the roads is important, but also its maintenance has a significant impact on the quality of the infrastructure. To reduce or prevent asphalt aging processes, effective maintenance must be applied. Nowadays, many factors influence the decision-making process of asphalt maintenance. For example, costs, environmental impact and safety.

This research identifies the impact of asphalt maintenance measures on sustainability and costs to support the decision-making process for the municipality Enschede-Losser, aligned with their policy objectives. The tool provides insight into the trade-offs between the integrated impact criteria for different maintenance measures. Its development involves a data gathering process, criteria integration and a structured design approach.

First, data is gathered regarding the asphalt mixtures and machinery that are used by NTP for asphalt maintenance. Both traditional and sustainable mixtures are used for different road layers. Next, the Environmental Cost Indicator (MKI) and $CO_2$ emission values are gathered and analysed revealing that sustainable mixtures score relatively better on these criteria than traditional mixtures. Finally, the costs of the asphalt mixtures per ton and the used machinery are gathered. This shows that not all sustainable mixtures are more expensive than traditional ones, depending on their lifespan. The data, sourced from internal documents and Ecochain reports, serves as input for the tool's calculations.

The tool integrates both quantitative (MKI, $CO_2$, costs) and qualitative (safety, availability) criteria. The qualitative criteria can be assessed manually by the user of the tool. The quantitative criteria are assessed by calculations of the tool. First, the total output per criteria is calculated for each measure. This value is converted to an annual value, facilitating fair comparison. The annual values are generalised and given a score between 1 (worst) and 5 (best), to be able to add them up and calculate a final score per measure.

The tool is developed in Microsoft Excel and has several design principles that shape its functionality. These are simplicity, flexibility, consistency, transparency and user friendliness. It consists of four main types of sheets. First, the dataset sheets including all the gathered data per criteria. Secondly, the calculation sheets, where the measures can be composed and their total and annual output per criteria is calculated. Thirdly, the 'fill-in' sheet, in which the user fills in the project specific characteristics such as the road dimensions and transport distance. Lastly, the dashboard sheet includes the trade off matrices and data visualisation charts to provide a clear overview of the assessment results, enabling users to compare different maintenance measures effectively.

The model verification including a sensitivity analysis is performed by slightly adjusting the input parameters to check whether the formulas are correctly implemented and the output changes as expected. The model validation is performed with a use-case by implementing the budget values of a real-life project from NTP. Also, a stakeholder is asked to test the model and validate the design principles. Both the verification and validation imply that the tool generates

accurate and reliable results. The relationships indicated by the conceptual model are correctly integrated and the validation accuracy is 87.8%.

In conclusion, the developed tool provides a structured and data-driven approach to evaluating asphalt maintenance measures by integrating both quantitative and qualitative criteria.

# Samenvatting

In de civiele techniek is het ontwerpen en aanleggen van wegen essentieel om efficiënte en veilige transportnetwerken te behouden. Wegen spelen een cruciale rol bij het verplaatsen van voertuigen van hun oorsprong naar hun bestemming. Niet alleen de aanleg van wegen is van belang, maar ook het onderhoud heeft een significante invloed op de kwaliteit van de infrastructuur. Om verouderingsprocessen van asfalt te vertragen of voorkomen, moet effectief onderhoud worden toegepast. Tegenwoordig beïnvloeden veel factoren het besluitvormingsproces rondom asfaltonderhoud, zoals kosten, milieu-impact en veiligheid.

Dit onderzoek identificeert de impact van duurzame en kosteneffectieve asfaltonderhoudsmaatregelen ter ondersteuning van het besluitvormingsproces voor de gemeente Enschede-Losser, in lijn met hun beleidsdoelstellingen. De tool biedt inzicht in de afwegingen tussen de geïntegreerde impactcriteria voor verschillende onderhoudsmaatregelen. De ontwikkeling van de tool omvat een dataverzamelingsproces, criteria-integratie en een gestructureerde ontwerpmethodiek.

Voor de dataverzameling is uitgebreide informatie verzameld over de asfaltmengsels en machines die door NTP worden gebruikt voor asfaltonderhoud. Zowel traditionele als duurzame mengsels worden toegepast voor verschillende wegdeklagen. Vervolgens zijn de waarden van de Milieu Kosten Indicator (MKI) en $CO_2$-uitstoot verzameld en geanalyseerd, waaruit blijkt dat duurzame mengsels relatief beter scoren op deze criteria dan traditionele mengsels. Tot slot zijn de kosten van asfaltmengsels per ton en de gebruikte machines verzameld. Dit toont aan dat niet alle duurzame mengsels duurder zijn dan traditionele, afhankelijk van hun levensduur. De gegevens, afkomstig uit interne documenten en Ecochain-rapporten, dienen als input voor de berekeningen van de tool.

De tool integreert zowel kwantitatieve (MKI, $CO_2$, kosten) als kwalitatieve (veiligheid, beschikbaarheid) criteria. De kwalitatieve criteria kunnen handmatig door de gebruiker worden beoordeeld, terwijl de kwantitatieve criteria door de tool worden berekend. Eerst wordt de totale output per criterium voor elke maatregel berekend. Deze waarde wordt vervolgens omgerekend naar een jaarlijkse waarde, wat een eerlijke vergelijking mogelijk maakt. De jaarlijkse waarden worden gegeneraliseerd en beoordeeld tussen 1 (slechtst) en 5 (best), waardoor ze opgeteld kunnen worden om een totale eindscore per maatregel te bepalen.

De tool is ontwikkeld in Microsoft Excel en is gebaseerd op verschillende ontwerpprincipes die de functionaliteit vormgeven: eenvoudigheid, flexibiliteit, consistentie, transparantie en gebruiksvriendelijkheid. De tool bestaat uit vier typen werkbladen. Allereerst de datasetbladen, die alle verzamelde gegevens per criterium bevatten. Ten tweede de berekeningsbladen, waarin de maatregelen worden samengesteld en hun totale en jaarlijkse output per criterium wordt berekend. Ten derde het invoerblad, waarin de gebruiker projectspecifieke eigenschappen invoert, zoals de wegafmetingen en transportafstand. Tot slot bevat het dashboardblad de trade-off matrixen en visualisatiegrafieken, die een duidelijk overzicht van de beoordelingsresultaten geven en gebruikers in staat stellen verschillende onderhoudsmaatregelen effectief te vergelijken.

De verificatie van het model is uitgevoerd door middel van een sensitiviteits analyse. De input parameters zijn lichtelijk verhoogd en verlaagd om te checken of de formules goed geimplementeerd zijn en of de output zich gedraagt als verwacht. De validatie van het model is uitgevoerd met behulp van een use-case door de begrotingswaarden van een real-life project van NTP in te voeren. Ook is een stakeholder gevraagd om de tool te testen voor het valideren van de ontwerpprincipes. Zowel de verificatie als de validatie tonen aan dat de tool nauwkeurige en betrouwbare resultaten genereert. De relaties die in het conceptuele model zijn vastgesteld, zijn correct geïntegreerd en de validatie toont een nauwkeurigheid van 87,8%.

In conclusie biedt de ontwikkelde tool een gestructureerde en datagestuurde benadering voor de evaluatie van asfaltonderhoudsmaatregelen door integratie van zowel kwantitatieve als kwalitatieve criteria.

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# Abbreviations and terminology

| | |
|---|---|
| AC | Asphalt Concrete |
| CBM | Condition-Based Maintenance |
| $CH_4$ | Methane |
| CM | Corrective Maintenance |
| CMA | Cold Mix Asphalt |
| $CO_2$ | Carbon Dioxide |
| EAB | Emulsion Asphalt Concrete |
| ECI (MKI) | Environmental Cost Indicator |
| GHG | Greenhouse Gas |
| GWW | Earth, Road, Waterworks sector |
| HMA | Hot Mix Asphalt |
| LCA | Life-cycle Assessment |
| LCCA | Life-cycle Cost Analysis |
| LCM | Least Common Multiple |
| MCDM | Multicriteria Decision-making Method |
| Municipality of Enschede-Losser | Municipality of Enschede and municipality of Losser |
| $N_2O$ | Nitrous Oxide |
| PM | Preventive Maintenance |
| PR | Partial recycling |
| RAP | Recycled Asphalt Pavement |
| RZR | Rood-Zwart-Rood |
| SCNA | Stage Class Not Acceptable |
| SMA | Stone Mastic Asphalt |
| TCO | Total Cost of Ownership |
| TNO | Dutch Organization for Applied Scientific Research |
| TOM | Trade-off Matrix |
| WMA | Warm Mix Asphalt |

# 1. Introduction

In the civil engineering field, designing and construction of roads is important to maintain efficient and safe transportation networks. Roads play a major role in moving vehicles from their origin to their destination. This includes smaller, single roads that need to be designed and constructed, up to entire intersections and highways that are being built. Not only the construction of the roads is important, but also its maintenance has a significant impact on the quality of the infrastructure. Proper maintenance of the asphalt ensures high quality roads that remain in good condition for a longer time. This also results in traffic being less hindered by poor road surfaces.

Basically, there are two general maintenance strategies that are mainly used: preventive maintenance and corrective maintenance (Johnson, 2000). These can also be applied to asphalt maintenance in different ways. This means that companies must make choices, often based on minimizing costs, decreasing time and ensuring quality. These goals are translated into criteria for a decision-making process. In recent years, these criteria have been increasingly influenced by climate change and sustainability concerns. Previously, the paving of asphalt was more focused on cost-efficiency. Nowadays, international climate agreements and government policies push the road construction industry also towards more sustainable practices using alternative materials and new production techniques (Ruiz, 2024). The shift gives more priority to asphalt maintenance becoming a more environmentally friendly process. This includes less $CO_2$ emissions and reducing environmental impact, reflected by the MKI (Environmental Cost Indicator) factor. The MKI is a single-score indicator expressed in euros. It combines all relevant environmental impacts of a product into a single environmental cost score that shows the environmental shadow price/shadow costs of the product or project (Hillege, 2024). However, it remains challenging to obtain clear, measurable results from sustainable maintenance measures. This is because many factors contribute to $CO_2$ emissions, including different material properties and production methods. This makes it difficult to determine whether a measure contributes positively to achieving the policy goals.

One main goal from the national government is to become $CO_2$ neutral in 2050. Therefore, the $CO_2$ emissions during the asphalt production and maintenance processes need to be decreased. Two companies, named NTP and Roelofs have accepted a contract from the municipality of Enschede-Losser regarding asphalt maintenance in the region. This research aims to identify sustainable and cost-effective asphalt mixtures and maintenance measures based on policy objectives from the municipality Enschede-Losser that contribute measurably to achieving their goals, by developing a tool that supports the decision-making process. In this proposal, the research objectives, questions and methods are outlined.

Therefore, chapter 2 will focus on the problem context and statement to clarify what needs to be investigated. Chapter 3 describes the plan of the research. This includes the research objective, scope and research questions. After that, the report dives into the methodology behind the research questions in chapter 4, followed by a literature study that discusses relevant findings related to sustainable asphalt maintenance in chapter 5. In chapter 6, the results of the research and the tool development are discussed. Chapter 7 includes the discussion of the results, followed by the conclusion in chapter 8. Finally, recommendations are given in chapter 9.

# 2. Research problem

This chapter elaborates on the context of the problem, including the problem statement. This includes a view on the state of the field, the explanation of the problem, involved parties and other key concepts.

## 2.1 Problem context

The municipality of Enschede-Losser wants to focus on achieving their objectives regarding climate change, a healthy environment and nature in the coming years (Municipality of Enschede-Losser, 2023). The objectives and approaches are shown in Appendix A. The municipality has its own organizational objectives, which are partly derived from the national objectives for 2030 and 2050 on these subjects. For the next eight years, both companies NTP and Roelofs have accepted the assignment of the municipality of Enschede-Losser regarding sustainable asphalt maintenance to reach the goals that are part of the request of the municipality.

NTP is a Dutch regional company that is active in the field of road, soil and water construction, but also in the field of energy and consultancy. They are committed to a sustainable and safe environment. Roelofs is a construction company, active in the field of area development, mobility, water, sewerage and resources. By developing and innovating, the company wants to 'add more value to the areas around'.

Two of the objectives from the municipality are reaching a $CO_2$ neutral environment and create a healthier environment. Asphalt maintenance can contribute to this by reducing the $CO_2$ emissions and lowering the MKI factor per asphalt mixture or maintenance measure. This is because many processes involved in this sector contribute to affecting the environment that influence the achievement of the two objectives from the municipality (Jiang, 2020). The construction and continuous road maintenance work consume large number of materials and fuel, which are produced through highly carbon-extensive processes (Santos et al., 2015). To become more sustainable, it must become clear what the $CO_2$ emissions are per asphalt type or measure.

## 2.2 Problem statement

The problem context given in chapter 2.1 is closely related to the shift in approaching the goals and criteria regarding asphalt maintenance in chapter 1. In both sections, it is mentioned that there is greater emphasis for an environmentally friendly process within asphalt maintenance. The difficulty is that different asphalt mixtures and maintenance measures have different impacts on $CO_2$ emissions and MKI. The use of different materials per measure could also lead to differences in costs since sustainable products are often more expensive due to the intensive research and development that is required. Innovative solutions for a more sustainable future are often paired with investments in new technologies, materials and production methods (Roggeveen, 2023).

There is a lot of data available about costs, MKI and $CO_2$ emissions that can be requested from the municipalities and companies. The problem is that maintenance decisions are made based on assumptions about their impact rather than on measured impacts and trade-offs. Both companies NTP and Roelofs propose maintenance measures to the municipality and need to demonstrate the sustainable benefits that can be achieved relative to the costs. The challenge is that the impact on criteria such as $CO_2$ emissions, MKI, and costs is often assumed rather than quantitatively substantiated. These assumptions can result in uncertainty about the actual impact of a measure, making it difficult to predict outcomes accurately and compare alternatives effectively. While increasing the accuracy of the assumptions and substantiations can reduce some uncertainties, they will remain. This complicates the decision-making process on asphalt maintenance, since Roelofs and NTP need to show the benefits of their measures despite the uncertainties, forcing decision-makers to make choices based on incomplete information about the environmental impact.

# 3. Research dimensions

This section elaborates on the framework of the research by describing and explaining the research objective, scope and research (sub)question(s).

## 3.1 Research objective

As mentioned in chapter 2.2, the research problem is that asphalt management decisions are being made more based on assumptions rather than on impact measures and their trade-offs. This complicates the decision-making process for choosing the most suitable maintenance measures to meet policy goals.

Therefore, the research objective is: *To design a tool that estimates the impact on MKI, $CO_2$ emissions and costs of asphalt mixtures and maintenance measures. The tool also intends to integrate the impact values into a trade-off matrix (TOM), supporting the decision-making process on asphalt maintenance.*

## 3.2 Research scope

The research scope ensures a high understanding of why certain parts are included or not in the research aim. In addition, since the bachelor thesis is done in ‘only’ 10 weeks, a clear definition of the scope is required.

The first significant element of the scope concerns which life stages of asphalt are involved in this project, also considered the life-cycle phases. In this research, the entire life-cycle of asphalt is considered. This includes the asphalt production, construction, use and disposal phase. The use phase is also considered the maintenance phase. This means that the values of the production and construction phase are used in the use phase as well, depending on the maintenance frequency and lifespan.

Secondly, the environmental impact perspective in this research includes both $CO_2$ emissions and MKI. When improving environmental impact, $CO_2$ emissions or MKI are reduced. Other factors, such as noise pollution are not included. Additionally, the $CO_2$ impact and MKI are included for each module. However, the specific actions or activities responsible for the impact within a module are not considered individually.

Thirdly, the timeframe of the scope can be considered as a relatively long period. Even though NTP and Roelofs will be responsible for asphalt maintenance in the region for eight years, the objectives from the municipality are set to be achieved ultimately in 2050. The thesis is performed with data obtained after 2020. This thesis examines a period of about 30 years.

Finally, the geographical scope is the area of the municipality Enschede-Losser. To specify, the research is done for main roads, rural roads and cycling paths.

## 3.3 Research questions

Based on the problem context and statement, two main research questions are formulated to achieve the research objective. These are stated below.

***1. What are the MKI, $CO_2$ emissions and costs of asphalt mixtures and maintenance measures during their life-cycle phases?***

This question focuses on determining the MKI, $CO_2$ emissions, and costs of asphalt mixtures and maintenance measures throughout their life-cycle phases. First it is determined which asphalt mixtures and materials are used for asphalt maintenance. Then the values of the quantitative criteria must be gathered. Only direct costs are included, such as machinery and material costs. Indirect costs such as designing and planning of the project are excluded. To provide the necessary input for the tool, the data must be collected for each phase of the life-cycle. This will allow for a clear overview of the MKI, $CO_2$ emissions, and costs associated with each asphalt mixture or measure in each phase.

***2. How can MKI, CO2 emissions, and costs be integrated into a trade-off matrix to assess asphalt maintenance measures?***

This question investigates how the decision criteria, essential for evaluating asphalt mixtures and maintenance measures, should be integrated into the development of the TOM-integrated tool. Specifically, it explores how both quantitative criteria (such as costs, MKI, and $CO_2$ emissions) as well as qualitative criteria (safety, availability, circularity and biodiversity), can be incorporated into a trade-off matrix within the tool. The qualitative criteria are not thoroughly investigated during this thesis, as these criteria are location dependent. However, they are briefly considered when creating the tool ensuring flexibility for users to add additional criteria when needed.

The included criteria must be in line with policy objectives and company demands. A proper definition and expression of the criteria and its units is needed to quantify and compare them. Adding an option to assign weights to the decision criteria ensures priority-based comparison, reflecting the relative importance of a criterion.

Based on the decision criteria, a TOM is created. This TOM is implemented in the tool and utilizes the data and measures to identify the trade-offs between the decision criteria. The tool assigns scores to the measures and visualises the data. This integration will enable systematic comparison and informed decision-making, considering both numerical data and qualitative criteria.

# 4. Research design

Chapter 4 provides the research methods used per research question. This will be followed by a literature study to investigate the current academic knowledge of the field.

## 4.1 Research question 1

The methodology of the first research question, described in section 3.3, is explained below. This question is mainly answered by requesting data from the companies and municipalities. Other techniques such as $CO_2$ calculation tools and reading through online websites and papers are used as well. The literature study is the first part of the methodology, performed in chapter 5. This study gives insights in which phases and materials the $CO_2$ emissions are produced.

The first step is collecting data about the asphalt mixtures and materials that are used during maintenance, so that these can be included in the tool. The materials can be divided into different elements. Below, the data categories and how they are collected are shown. The data is put in different Excel sheets per category, so that the corresponding values of the quantitative criteria can be added.

**Asphalt mixtures**

- **Excel file** '*asfaltonderhoudsmaatregelen*', received from NTP, Appendix B, figure B.1

**Asphaltsets, machinery and personnel**

- **Excel file** '*Tarieven personeel 2023 (wijziging per 9 januari 2023)*' received from NTP, Appendix B, figure B.2

**Transport vehicles**

- **Excel file** '*Tarieven personeel 2023 (wijziging per 9 januari 2023)*' received from NTP, Appendix B, figure B.2
- **Website** '*bouwemissies.nl'*

The second step is to collect the MKI values per asphalt mixture and life-cycle phase. The tool mainly uses phases A1-A3 and D. To visualise this, the phases in which MKI values can be calculated, are shown in figure 1.

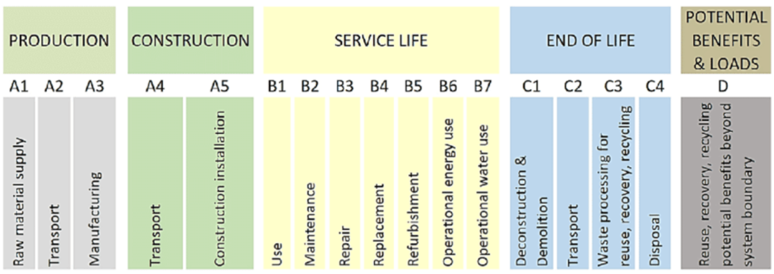


*Figure 1: Life-cycle phases A-D show which elements impact the MKI value of a life cycle*

The MKI values are collected from multiple documents, shown below. These values are added to the MKI dataset sheet in Excel. Some of the PDF files in the next steps contain confidential information and are thus not completely available for reading purposes.

- **PDF report** '*LCA Achtergrondrapport voor Nederlandse branchereferentiemengsels 2022*', page 53-68, received from NTP, produced by Ecochain. **Database:** ecoinvent v3.6
- **PDF file** '*Productinformatieblad Ecofalt 11 surf*', received from Ecofalt, LCA produced by Ecochain. **Database:** ecoinvent v3.6 (Confidential)
- **PDF files** produced by '*NTP Groep BV - Asfalt Centrale Bovenveld - PCR asfalt 2.0'*, received from NTP, LCA's produced by Ecochain. **Database:** ecoinvent v3.6 (Confidential)
- **LCA calculations** received from Roelofs via personal communication. **Database:** DuboCalc

The third step is gathering the $CO_2$ emissions per ton asphalt mixture. The same method is used as in the second step. The emissions of the asphaltsets, machinery and transport vehicles are gathered via the 'TNO bouwemissietool'. TNO is the Dutch organization for applied scientific research (Bouw emissie tool, 2025). This tool calculates the emissions per hour and kilometre for the machinery and transport. These values are added to the $CO_2$ dataset sheet in Excel.

The last step is to determine the total costs per life stage. Data must be gathered on the costs of the asphalt mixtures and materials that are used in the tool. The costs per category and how they are collected are shown below. These values are added to the cost dataset sheet in Excel.

**Asphalt mixtures**
- **PDF file** '*prijzen ACB 10062024*' received from NTP (Confidential)

**Asphaltsets, machinery and personnel**
- **Excel file** '*Tarieven personeel 2023 (wijziging per 9 januari 2023)*' received from NTP, Appendix B, figure B.2
- **PDF file** '*Aduco Asfaltfreestarieven 1 April 2024*', received from NTP, supplied by Aduco (Confidential)
- **PDF file** '*Appeldoorn tarieven*', received from NTP, supplied by Appeldoorn (Confidential)
- **PDF file** '*v Werven-NTP'*, received from NTP, supplied by Van Werven (Confidential)

**Transport vehicles**
- **Excel file** '*Tarieven personeel 2023 (wijziging per 9 januari 2023)*' received from NTP, Appendix B, figure B.2
- **Online websites** including hourly rates to use as indication price

## 4.2 Research question 2

The second research question concerns the process of integrating the obtained values concerning MKI, $CO_2$ and costs into a TOM, and finally design a tool for the assessment of maintenance measures.

The first step in integrating the criteria into the tool is to standardize the measurement units, ensuring that each criterion can be converted to one total value. Calculation sheets are created to aggregate $CO_2$ emissions from different sources (per hour, day and kilometre). In addition, these total values are converted to annual values to account for the lifespan of each measure. This allows the tool to generalise the scale of the criteria to make options comparable. By adding an option to assign a weight to a criterion, the criteria are integrated reflecting the user's values.

The next step is formulating the design principles required for the tool's development. These principles include simplicity, consistency, transparency, user-friendliness and flexibility. Clear guidelines improve both the technical and functional aspects of the tool.

Thirdly, a TOM is created as part of the dashboard in which the criteria are integrated. Also, a fill-in sheet will be developed to fill in some project-specific characteristics such as layer thicknesses and transport distances. Finally, the generalised scores in the TOM are visualised by creating charts to allow the user to compare the measures effectively.

The final step involves the model verification and validation. For the verification, a sensitivity analysis is performed to evaluate how changes in inputs affect the outputs of the tool. For the validation, a project's use-case from NTP is taken to compare results of the tool with real-world data, checking the reliability and accuracy of the tool. The design principles are verified and validated by asking stakeholder's to test the tool and reflect on to what extent the principles are implemented correctly. After that, a budget plan from NTP is compared with other measures in the tool to assess how it can improve the asphalt maintenance decision-making.

## 4.3 Research matrix

This subchapter aims to offer an easy format on how to view the research project. In table 1 below, the research matrix is shown. The important aspects of the project are shortly written down.

*Table 1: Research matrix*

| **Research question** | **Why** | **Methods** | **Data** | **Timeline** |
|---|---|---|---|---|
| What are MKI, $CO_2$ and costs of mixtures and measures?<br><br>Question 1 | Determine impact of asphalt mix and measures on criteria | Data gathering and analysis on sub-question 1.1, 1.2, 1.3 and 1.4, Data orientation | NTP, Roelofs, Municipality of Enschede-Losser | After answering the steps of research question 1 |
| What are the mixtures and materials?<br><br>Step 1.1 | Determine mixtures and materials included in tool | Request documents from companies and municipalities | NTP, Roelofs, TNO | Starting phase of thesis |
| What are the MKI values?<br><br>Step 1.2 | Determine the MKI values per life stage | Request from companies and municipalities, Company documents | NTP, Roelofs, Municipality of Enschede-Losser | Starting phase of thesis |
| What are the $CO_2$ emissions?<br><br>Step 1.3 | Determine total $CO_2$ emissions during life stages | Request from companies and municipalities, LCA tool | NTP, Roelofs, Municipality of Enschede-Losser, TNO | Starting phase of thesis |
| What are the costs?<br><br>Step 1.4 | Determine total costs during life stages | Online websites, Request from companies and municipalities | NTP, Roelofs, Municipality of Enschede-Losser, | Starting phase of thesis |
| How criteria integrated to assess measures<br><br>Question 2 | Gain insight in how the tool should be developed | Create TOM, Evaluate criteria, Define scenarios, Identify trade-offs | TOM, Received data from sub-questions 2.1 and 2.2 | After answering step 2.2 |
| How should criteria be integrated in TOM?<br><br>Step 2.1 | Determine included criteria and units in TOM | Request company, Define units, Account for lifespan | NTP, Roelofs, Municipality of Enschede-Losser | After answering research question 1 |
| How should the tool be designed?<br><br>Step 2.2 | Give insight in he steps needed for creating the final tool | Integrating TOM, Data comparison, Data visualisation, Excel software | NTP, Roelofs, Municipality of Enschede-Losser, TOM | After answering step 2.1, Final phase of thesis |

# 5. Literature study

It is important to study existing literature on the topic to find relevant and helpful information for the research. This gives insight in understanding different interpretations of concepts.

## 5.1 Maintenance strategies

A maintenance strategy is a structured approach to preserving equipment, involving activities such as identifying issues, analysing maintenance options, and carrying out repairs, replacements, and inspections. Effective implementation of the strategy requires concrete and tactical action plans (Velmurugan & Dhingra, 2015). Additionally, a maintenance strategy consists of a series of policies and actions aimed at preserving or restoring equipment. It also includes a decision support system that helps plan maintenance activities (Shafiee & Sørensen, 2017). Another definition of a maintenance strategy is an integrated system that is essential for corporate management to emphasize the importance of specific equipment that influences certain types of maintenance activities. (Rani et al., 2015). These definitions are slightly different in wording, but are commonly focused on structured planning. The main difference is whether the strategy focuses mainly on practical, separate tasks for maintenance or takes a broader view, making maintenance part of the overall business decisions. This means a good maintenance strategy needs clear, detailed plans for how things should be done, as well as a connection to the company's bigger goals. For the research assignment, the last definition is important to consider since NTP and Roelofs also have sustainable objectives to achieve that must be considered when decisions are made on what maintenance measure will be implemented. So, besides only performing a measure for repair, maintenance must also align with the broader company goals, such as becoming climate neutral in 2050.

In (Lee & Scott, 2009, Shin & Jun, 2015) the following maintenance categories are described: preventive maintenance (PM), corrective maintenance (CM) and condition-based maintenance (CBM). In (Ollila & Malmipuro, 1999), even four maintenance categories are mentioned. The authors discuss four main maintenance strategies: reactive, preventive, predictive, and proactive. Preventive maintenance involves scheduling maintenance activities at regular intervals to prevent failure. Predictive maintenance relies on identifying faults before a breakdown occurs, using techniques such as monitoring and diagnostics. Proactive maintenance focuses on improving current infrastructure to address underlying issues rather than just preventing immediate failures. In contrast, reactive maintenance, which deals with problems only after they arise, is generally considered less effective and should be replaced by more forward-looking strategies to enhance reliability and efficiency. This is important to consider since the tool is mainly used to apply corrective or reactive maintenance. By incorporating the lifespan of the measures in the tool, predictions can be made about the condition of a road, allowing for the development of more forward-looking strategies, such as preventive maintenance. According to Ollila and Malmipuro (1999), these proactive strategies are more effective in the long run.

Vaitkus et al., (2016) describe the concept of preventive maintenance more as a type of maintenance that is used to increase sustainability, instead of only being cost-effective. It is stated that a shift towards more preventive maintenance is important to solve multiple problems that countries are dealing with. These problems include budget and time constraints, as well as environmental impact. However, this author also writes that the difficulty of preventive maintenance is the long-term planning and the huge number of data analyses are needed to create a well-designed preventive maintenance plan.

Stenström et al., (2015) indicate that preventive maintenance (PM) typically represents about 10% to 30% of the total maintenance costs. The Cost-Benefit Analysis that the benefits of implementing preventive maintenance significantly outweigh the costs. This analysis supports the conclusion that corrective maintenance is generally more expensive than PM, highlighting the value of investing in preventive strategies to enhance overall maintenance efficiency and reduce long-term costs. The concept of preventive maintenance is clearly considered as a cost-effective maintenance method, if it is performed in the right way. In conclusion, preventive maintenance (PM) emerges as a key strategy for offering significant cost savings and environmental benefits. Unlike reactive maintenance, which deals with issues after they arise, PM focuses on maintaining constructions when it is still in good condition. This approach extends the lifespan of assets, reduces overall costs, and minimizes carbon emissions and energy use. However, implementing PM requires careful planning and substantial data analysis, making it more complex to execute than traditional methods. Haider and Dwaikat (2011) emphasize that the timing of pavement maintenance is a key factor influencing both its effectiveness and cost-efficiency. Implementing maintenance at the optimal moment ensures that treatments are applied before major deterioration occurs, extending pavement lifespan and reducing overall agency expenses. Traditional maintenance methods often lack precise timing guidelines, relying more on experience than data-driven decision-making. Despite these limitations, adopting preventive and proactive maintenance strategies is essential for long-term efficiency and sustainability. Incorporating the lifespan of maintenance measures into the tool’s development could improve the prediction of maintenance needs, optimizing timing to enhance cost-effectiveness and minimize environmental impact (Stenström et al., 2015). This contributes to achieving the goals of NTP.

## 5.2 Asphalt maintenance

Pavement maintenance is carried out to preserve, restore, or improve the functionality of road surfaces. It is mainly done on roads that have weak structures and damaged surfaces. Poor road maintenance can lead to higher vehicle costs, reduced mobility, more traffic accidents and related expenses, and can contribute to problems like poverty, isolation, low literacy rates, and poor health, especially in rural areas. (Burningham & Stankevich, 2005). When maintaining road assets, balancing the cost of maintenance with the quality of highway service is a key priority. Pavement maintenance decisions often involve multiple factors, including policies, financial constraints, road damage, and environmental requirements, making them complex and multifaceted (Liu et al., 2016). A study conducted on preventive maintenance claims that preventive maintenance is a major strategy that can significantly contribute to the sustainability of asphalt maintenance. The traditional approach to pavement maintenance primarily relies on corrective maintenance. However, this method often fails to address issues at the optimal time, allowing pavement deterioration to become worse. As a result, maintenance costs, carbon emissions, and energy consumption increase. (Xu et al., 2024).

Pavement preventive maintenance involves applying cost-effective measures to well-maintained roads without increasing the strength of the pavement structure. The goal is to keep the pavement in good condition, delay damage, and maintain or improve its function (Li et al., 2021). This article explains that preventive maintenance is a more cost-effective option. Both sources agree that this maintenance is done when the road is still in good shape or has only minor issues. By doing so, it extends the road's life and reduces the overall costs of more expensive corrective maintenance later on.

Pavement preventive maintenance treatments focus on preserving, rather than enhancing, the structural capacity of the pavement. These treatments should be applied before significant damage, such as cracks and distresses, appear. The main goal of this type of maintenance is to remain cost-effective. (Zaniewski, 1996). This is in line with the definitions mentioned before. A detailed analysis shows that materials with higher viscosity, cohesion, and adhesion provide the best performance as preventive maintenance materials for porous asphalt pavements. Therefore, it is recommended to consider these properties, such as apparent viscosity, cohesion, and adhesion, when selecting a preventive maintenance material for porous asphalt. (Xu et al., 2018). By incorporating this, the tool can offer more precise recommendations about material selection for maintenance that improve pavement longevity and performance.

To create a sustainable approach to pavement maintenance, it’s important to identify the most critical areas of the road that need repairs. This process is complex and sensitive, as it involves considering many factors (Marovic et al., 2018). In asphalt maintenance, life cycle assessment (LCA) is an important tool that helps with decision-making by assessing the long-term impacts of maintenance strategies. LCA is used to calculate the environmental impact, such as $CO_2$ emissions, of asphalt mixtures. The road industry is increasingly using LCA to evaluate and compare the environmental effects of products and construction methods, and to use this information for reviews or labeling (Huang et al., 2009). Therefore, effective asphalt maintenance is key to keeping roads functional and safe, while also reducing costs and environmental impacts. Choosing durable materials with high viscosity, cohesion, and adhesion improves preventive maintenance results. Identifying critical repair areas is important, but it requires balancing both technical and social factors.

## 5.3 Greenhouse gas emissions in asphalt maintenance

Asphalt pavement maintenance aims to reduce costs and environmental impact while generating economic and social benefits. However, the maintenance process itself can also create significant environmental burdens, including energy consumption and greenhouse gas (GHG) emissions. As a result, evaluating the environmental impact of asphalt pavement maintenance has become an increasingly important consideration (Huang et al., 2009). The oxidation of hydrocarbons in asphalt binder results in the production of carbon dioxide ($CO_2$) during the manufacturing of hot mix asphalt. Temperature appears to be the primary factor influencing $CO_2$ emissions (Mallick & Bergendahl, 2009). The European Asphalt Pavement Association (EAPA) highlights that most $CO_2$ emissions from asphalt pavements occur during the initial construction phase, due to the high temperatures needed for mixing and paving (EAPA, 2004). In the transportation phase, the distance travelled for specific projects significantly impacts energy consumption and $CO_2$ emissions related to maintenance measures (Yu et al., 2018). According to (Deng & Chen, 2002), generally, hot mix asphalt is used for paving roads, emitting large quantities of $CO_2$, $CH_4$, and $N_2O$. In figure 2, part of the production and construction process of asphalt mixtures is shown with their carbon flows. These flows must be considered when designing the tool since the production and construction phase are part of the research scope.

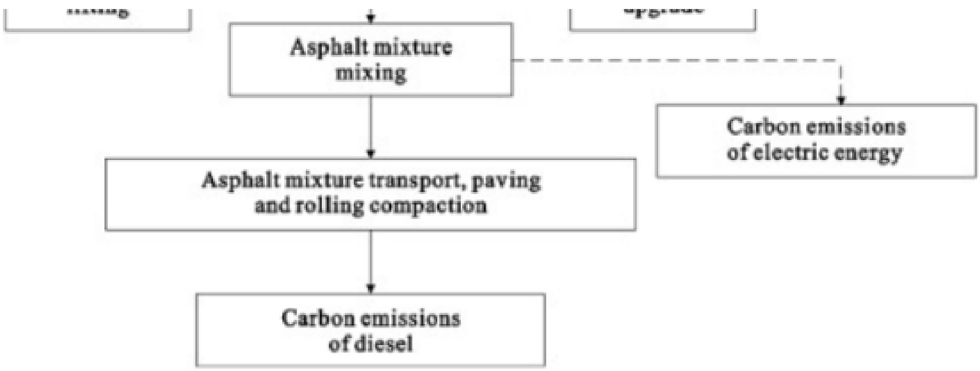


*Figure 2: Part of the production and construction process of asphalt mixtures including carbon flows (Peng et al., 2015)*

## 5.4 Decision-making in asphalt maintenance

Road maintenance decision-making is a complex process, since it requires to consider various factors. In a study from Huang et al. (2023), it is mentioned that asphalt maintenance decision-making can be done by using the decision tree method. This method ranks the significance of various indicators related to pavement maintenance. Ranking or weighting the criteria used in the tool could help identifying the significance of them. It is also mentioned that the selection of appropriate decision indicators is crucial. Considering this during the assignment is therefore a crucial step in the development of the tool. The maintenance decision-making system from Huang et al., (2023) has undergone rigorous validation through case studies, demonstrating its applicability and rationality in real-world scenarios. Including a use case validation method in this report can improve the reliability of the tool that is built.

Another study by Pamukovic (2020) discusses a different MCDA method for making decisions, called the analytic hierarchy process (AHP). This method creates a ranking list based on different solutions that are evaluated according to certain criteria. In this case, the different solutions would be various maintenance measures, and the criteria could include MKI, CO2 emissions, safety, and others. It's also explained that higher weights mean a criterion is more important, while lower weights mean it's less important. The final ranking is made by combining the weights of the criteria with the scores of the different solutions. In AHP, the weights are defined based on pairwise comparisons. However, this is not the case when using a TOM.

Li et al. (2021) describes a decision-making method mainly based on deep learning. The method is called Artificial Neural Networks (ANN). It is used to analyse data and provide maintenance advice offering precise recommendations for maintenance measures needed at specific locations along the highway, making it a direct decision-making tool for highway maintenance. Suwarto et al. (2023) mention Life-cycle cost analysis (LCCA) to be a structured approach to decision-making in asphalt maintenance. LCCA considers the total costs of a pavement section over its entire life cycle, including construction, maintenance, and removal. By evaluating the costs of different maintenance and rehabilitation options, LCCA can help identify the most cost-effective maintenance option for asphalt.

Although the decision tree method is used to rank various indicators, this method is too superficial and does not offer enough quantification of the decision-criteria. The implementation of a TOM could help by identifying the impact on the ranked criteria as it also contains real-life data. The AHP method is quite a complex method as it requires pairwise comparisons of the criteria based on mathematical models. The TOM is therefore a simplified option since the user can assign weights separately to each criterion. The resulting matrix could be more user-friendly as it is easier to analyse instead of the complex calculations in AHP. Additionally, NTP and Roelofs demand quick comparison of measures. Both the ANN and TOM are data-driven models. However, the TOM also works with limited data and is manually evaluated, while the ANN method requires large amounts of historical data to automatically predict the correct decision. The LCCA is a very useful method to gain insights in the costs of a measure. However, impact on other criteria is excluded here. A trade-off matrix allows evaluation of costs and other decision criteria. This allows NTP and Roelofs to quickly identify the impact on their maintenance measures based on their desired criteria. Therefore, the TOM is considered the most suitable method for the research.

# 6. Results

This section will discuss the results of this thesis. First, the results of the data gathering process are discussed, which is related to research question 1. Secondly, the development and designing of the tool is displayed, related to research question 2.

## 6.1 Overview of asphalt mixtures, machinery and impact criteria

Chapter 6.1 shows the results of the data gathered for research question 1. This includes the values of the MKI, $CO_2$, and costs of the categories asphalt mixtures, machinery, transport and personnel.

### 6.1.1 Asphalt mixtures, transport and equipment

This section contains the results of determining which mixtures, transport and other equipment must be included in the tool. The collected data is shown per category in a table in Appendices C up till F.

**Asphalt mixtures**
The asphalt mixtures that are included in the tool are requested from employees from NTP. Using figure B.1 from Appendix B, a list has been created showing the asphalt mixtures that NTP has available for asphalt maintenance. The list distinguishes between the top layer, intermediate layer and base layer of a road and is shown in Appendix C. Based on these mixtures, various measures can be compiled in the tool, allowing NTP to compare measures including all their asphalt mixtures. The different types of mixtures are shortly enlightened below.

AC 16 Bind is an intermediate layer mixture of asphalt concrete where the '16' indicates the minimum and maximum thickness of the layer. This would be 40mm to 60mm for AC 16 Bind (Rijkswaterstaat, 2022). AC 11 Surf also has its own thickness.

LynPave is a form of asphalt that has been developed to produce and process asphalt at a lower temperature (WMA). In addition, LynPave has a positive effect on the resistance to fatigue, which extends the lifespan of roads and reduces maintenance costs (NTP, 2024).

Grasfalt® is an asphalt mixture in which 50% of the binder consists of bitumen and 50% of lignin from the Miscanthus Giganteus crop, also known as Elephant Grass. In principle, any regular asphalt mixture can be produced in the form of Grasfalt® (NTP, 2024).

Ecofalt is the most sustainable alternative to regular hot asphalt and has the same external characteristics. What makes Ecofalt unique, is that it is produced at ambient temperature, so without heating. This results in a 100% reduction in gas consumption and $CO_2$ emissions during production. The sub- and intermediate layers of Ecofalt consist of 100% old road surface. As a result of our sustainable thinking, Ecofalt has solutions and functionalities that regular hot asphalt does not have (Ecofalt, 2023).

Stone Mastic Asphalt (SMA) is an asphalt pavement consisting of a high percentage of broken material of 2 mm and larger. The hollow spaces are filled with mastic: a composition of sand, filler and bitumen. SMA is slightly noise-reducing, is resistant to heavy axle loads and braking traffic, but is also very durable (AsfaltNu, 2024).

**Asphaltsets**
NTP uses standard asphaltsets including machinery and personnel for their maintenance. For example, cycling path set large or small that include asphalt pavers, vibratory rollers, bitumen trucks and executors. Selecting an asphaltset in the tool means that the user indirectly selects multiple machines and employees to be included in the maintenance measure. These sets are collected via NTP from the Excel file mentioned in section 4.1, from 2023. This means that they may have changed slightly in the meantime, but it does not affect the working of the tool. The remaining sets are shown in table C.2 in Appendix C.

**Machinery**
Within asphalt maintenance, several standard machines are commonly used, each serving a specific role in the maintenance process. Think of asphalt pavers for laying the asphalt and milling machines for removing asphalt. The ones that must be included in the tool, are supplied by NTP, as part of the asphalt sets above. For several machines, certain powers have been assumed that are most common. This is later used for the $CO_2$ calculations. Some of the machines come from NTP, also some from the internet. This does not make much difference for the operation of the tool. The machinery included in the tool is shown in Appendix C, table C.3.

**Transport and personnel**
In principle, three types of vehicles are needed for transport within asphalt maintenance. These are cars, buses and trucks. Cars are mainly used for transporting personnel and small equipment to and from the construction site. Buses can be used to transport larger groups of workers and small equipment efficiently, while trucks are essential for carrying heavy materials such as asphalt and construction machinery. The TNO tool distinguishes between cars and buses that run on gasoline or diesel. Both are included to let the user determine this for a specific project. In terms of personnel, an asphalt coordinator, employee, executor, finisher and machinist are included, also received from the asphaltsets.

### 6.1.2 MKI values

The MKI calculates the environmental impact of a product or process through a life cycle assessment (LCA). Emissions such as $CO_2$ and $NO_x$ are categorized into impact categories such as climate change and toxicity and converted into costs (€) based on shadow prices. By summing these costs, a single MKI score is generated, representing the total environmental costs (Hillege, 2024). The MKI calculations include the environmental impact from all life-cycle stages, such as raw material extraction, production, transport, construction, maintenance, and end-of-life. These stages cover factors like energy consumption, material usage, emissions, and waste generation.

In relation to step 2 of research question 1, the MKI values per life-cycle stage are shown in Appendix D, table D.1 The table includes the values per asphalt mixture and distinguishes between the road layers. From the methodology in section 4.1, the MKI's (mostly from '*LCA Achtergrondrapport voor Nederlandse branchereferentiemengsels 2022*', page 4) are calculated based on the Nationale Milieu Database (NMD) version 3.4 and 3.5, and database Ecoinvent 3.6. The LCA's are performed by Ecochain in private. In Appendix I, the sources from which the MKI (and lifespan) values were obtained can be seen. Blank cells mean that the values are not yet available.

### 6.1.3 $CO_2$ values

In relation to step 3, the $CO_2$ values per asphalt mixture and life-cycle stage are shown in table E.1. The table also distinguishes between the road layers. Furthermore, the $CO_2$ emissions of the machinery and transport equipment is calculated using the TNO tool (Bouw emissie tool, 2025) and is shown in Appendix E. This tool has its own database regarding the earth, road, waterworks sector (GWW). It allows the user to select a specific machine, such as a mobile crane. By filling in the power (kW), construction year and fuel class (stage class), the emission per hour in tons of $CO_2$ is calculated. The emissions are given in kilograms of $CO_2$ equivalents per life-cycle stage. Some cells state 'scna', which means 'stage class not acceptable'. This means that for the corresponding construction year, no values are available. In Appendix J, the sources from which the $CO_2$ emissions are gathered per category are shown. The low loader, site hut and water tank are considered as zero emission items.

### 6.1.4 Costs

In relation to step 4, the costs of the asphalt mixtures, machinery and transport are gathered. In Appendix F, the price per unit of the asphalt mixtures is shown, as well as the costs of the machinery, transport, personnel and complete asphalt sets. In Appendix K, the sources on which the costs are based are shown. For example, the standard AC 11 surf costs around 80 euros, while the red variant costs over 150 euros. These significant differences are important to consider when total project costs are calculated.

## 6.2 Tool development

Section 6.2 focuses on the step-for-step development of the tool, related to research question 2. The main purpose of the tool is to support the decision-making process of asphalt maintenance, by identifying the impact on multiple criteria for different measures. The tool is created and developed in Microsoft Excel. This is because Excel offers the possibility to process a lot of data, doing calculations on it by implementing difficult formulas, create a matrix including outputs and visualize the results in charts or diagrams. First, the general structure of the tool will be explained. Secondly, the criteria integration is explained. Next, the design principles are discussed and for each component of the tool a more substantive explanation is provided.

The general composition of the tool consists of:

- Dataset sheets of the criteria (input)
- Calculation sheets of the criteria (generating output)
- Fill-in sheet (generating input)
- Dashboard sheet (output visualization)

The dataset sheets contain data about the MKI, $CO_2$ emission and cost values that function as input for the tool. For each quantitative criterion, a separate calculation sheet is developed where the input is used to calculate the output values for each measure in the TOM. The fill-in sheet allows the user to fill in some general characteristics, such as the asphalt density or transportation distance. This way, transportation time and costs can be calculated as well in the calculation sheets. Finally, the dashboard sheet includes the TOM's including the final output of the calculation sheets. The TOM's include the total values of the criteria per measure, but also per year. Next to that, a TOM is created that has generalized the values of the criteria per measure and sums them up. This way, a general score is applied to the measures. These scores can then be visualized and compared to support the decision-making process.

## 6.2.1 Criteria integration

The first step in the development of the tool is the integration of the decision criteria. There are basically two types of criteria that will be part of the tool. The first type is quantitative, and the second type is qualitative. The quantitative criteria are needed to support the decision-making process based on real life data. The qualitative criteria are used to add a subjective value to a certain measure to strengthen or weaken the measure based on what the user prioritises. New criteria that will become more important in decision-making in the future can be added to the tool, as it offers room for expansion. The two types of criteria and how they are integrated in the TOM is explained below.

**Quantitative criteria**
The MKI, $CO_2$ emission and costs will be numerically integrated in the TOM on the demand of NTP and Roelofs. For the project of the municipality Enschede-Losser companies must be able to substantiate their decisions with numbers and real-life data. For both MKI and $CO_2$ emission, only modules A1-A3 and D are included in the TOM, since modules A4, A5, B and C are not yet calculated for multiple asphalt mixtures. However, they can be easily added to the tool when they are calculated in the future. MKI is calculated in euros per ton asphalt mixture, converted tot total euros per measure (per year). $CO_2$ is integrated in total tons of $CO_2$ in the TOM (per year). The costs are also integrated into the TOM as total costs per measure (per year). This requires additional calculations by the tool, because some costs are calculated per ton of asphalt or per hour of machine usage. Additionally, $CO_2$ emissions are sometimes provided per hour and sometimes per kilometre. These calculations are explained in section 6.2.5.

**Qualitative criteria**
Safety and availability are the two qualitative criteria that are integrated in the TOM. Qualitative criteria are also important for the decision-making process. For example, a strong numerical substantiation of MKI and costs can be dismissed if the safety of the measure is not guaranteed. There may be several qualitative criteria that can influence the decision, depending on the location of the measure. Currently, two qualitative criteria are included in the TOM to indicate that not only quantitative criteria are decisive. The tool allows the user to add additional qualitative criteria when desired.

**Functionality of criteria in the TOM**
The purpose of the TOM is to identify trade-offs between different measures based on the decision criteria. Multiple TOM's will be developed, each with slightly different functionalities. The first TOM contains the total output of the criteria per measure, showing the first impression of the impact of a measure. The second TOM is identical to the first, but includes the output per year, accounting for the lifespan. This ensures a fair comparison of the measures. The user can adjust the weighting of a criterion based on the project's priorities. This is applicable to all TOM's. The third TOM uses a generalised scale of 1 to 5 for each criterion, allowing for the aggregation of the criteria scores into a single overall score for each measure. This was not possible when costs in euros and emissions in kg $CO_2$ had to be directly summed. The measure with the lowest score on each criterion is assigned a 1, and the remaining values are scored up to a maximum of 5, based on the minimum acceptable value, which will be 0 for the quantitative criteria. These total scores per measure can then be compared and visualised by the tool to identify the impact of each measure, made possible by the TOM.

### 6.2.2 Design principles

This section covers the design principles of the tool, to create higher understanding of why and how the sheets are designed.

During the development of the tool, some key principles play an important role. These principles influence the way the tool is designed and why certain elements are (not) included. Below, the design principles and short explanations of their impact on the design are given.

**Simplicity**
The design of the tool is kept quite simple and abstract to avoid confusion. Especially, since the designer is not the only person using the tool. This does not mean that many details are left out, but the layout of the design is kept simple. This includes clear labels, titles and handy use of colours.

**Consistency**
To avoid even more confusion, consistency is important when designing the tool. Different elements with the same function must work in a similar way. This includes maintaining uniform formulas, table layouts and charts, as well as consistent colour schemes.

**Transparency**
Difficult calculations and formulas must be understandable for the user. Therefore, complex cells or calculations are enlightened or performed in multiple steps. Also, the cells including data are linked to the source the data is received from.

**User friendly**
The tool is designed with clear instructions, making it accessible for users with various levels of knowledge, including providing a manual.

**Flexibility**
The tool must be designed flexible for multiple reasons. High flexibility improves the accessibility of the tool since users with different knowledge levels will use the tool. By leaving room for extension, the tool offers high flexibility for users that want to work with different scenarios or extend the tool in the future.

### 6.2.3 Conceptual model

Section 6.2.3 covers the conceptual design of the tool for a maintenance measure. The purpose of this model is to break down the complexity of the design into understandable components. A simple structure of the tool is given in five different sub-models in figure 3. These can be used again during the model verification and validation. The relationships between the sub-models are visible as well, indicated with + and – signs. When the input data increases, the total output of the model increases as well. Increasing this total output results in an increase in annual output as well. An increase of the annual output results in a decrease of the generalised output. Therefore, these sub-models are negatively related. Then finally, the generalised output and final output is positively related again.

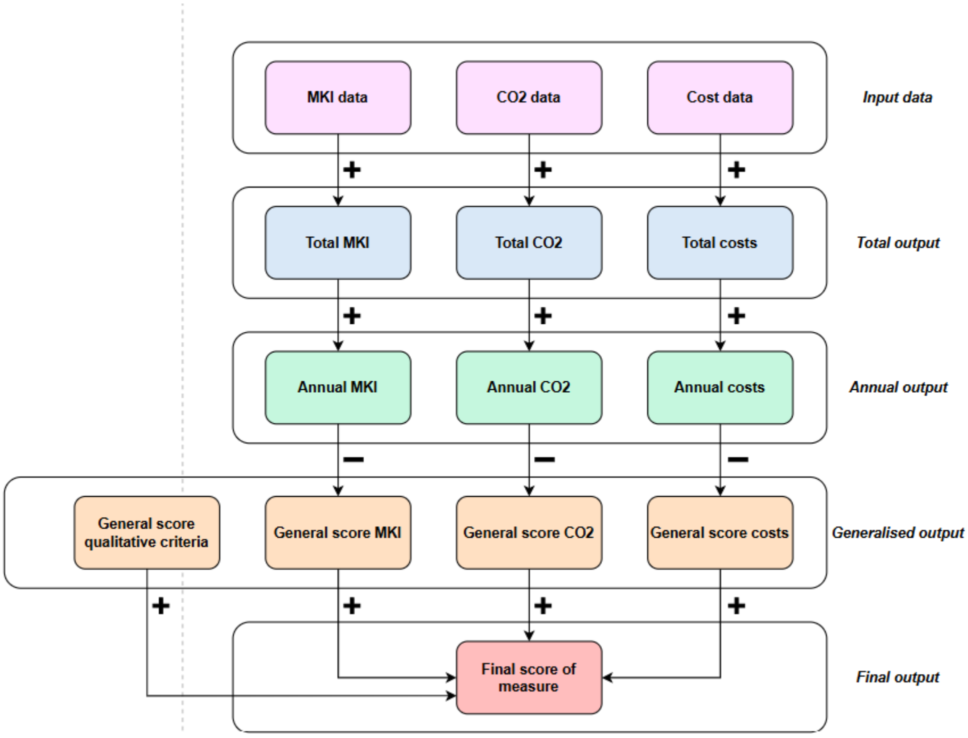


*Figure 3: Conceptual model of the maintenance tool*

### 6.2.4 Dataset sheets

Section 6.2.4 elaborates on the development of the dataset sheets per criteria.

**MKI**

For the MKI criterion, two datasheets are developed. These are shown in figures G.1a and G.1b in Appendix G.1. The datasheet in figure C.1a is developed to function as input for the calculation sheets. The sheet includes the MKI values in euros per ton asphalt mixture per layer. Also, the values are displayed per life-cycle module. This is because it differs per mixture which modules are calculated or not.

The blank cells indicate that the MKI value of that module is not yet known and could thus not be requested and included in the tool. The values are given per unit, which is mostly per ton asphalt. A margin column is added where the user can add a percentage to absorb uncertainty. The datasheet in figure C.1b is developed to include the lifespan of the asphalt mixtures in the output calculations. This sheet is mainly used as input for formulas in other sheets.

**$CO_2$**

For the $CO_2$ criterion, two datasheets are developed as well. Figure G.2a in Appendix G.2 shows the first datasheet, functioning as input for the calculation sheets. The first sheet includes the $CO_2$ emissions in kg per ton asphalt mixture per layer. Again, the values are displayed per module and the blank cells indicate that the $CO_2$ value of that module is not yet known and could thus not be requested and included in the tool. The columns A1-A3 and D are used in the calculations.

If the missing values become known in the future, these can be added to the tool. Figure G.2b shows the $CO_2$ emissions per asphaltset and per machine. The values are slightly different due to the different construction years. Lastly, figure G.2c shows the $CO_2$ emissions per transport type per road category depending on fuel type Euro 5 or Euro 6. These values function as input for the calculation sheet and are retrieved from the TNO tool.

**Costs**

For the costs, also two datasheets are developed. These can be seen in Appendix G.3, figures G.3a, G.3b and G.3c. They again function as input values for the calculation sheets. The first sheet contains the price in euros per unit of asphalt mixture for each layer.

The second sheet contains the costs of the asphaltsets, machinery, transport and personnel. These are given in price per day or hour. This can be converted to a total price per measure in the calculation sheets by determining the total days or hours a maintenance measure takes.

### 6.2.5 Calculation sheets

The calculation sheets are also divided into the criteria. For each criterion, two sheets are developed. The first sheet contains the calculations of the total values of the criteria per measure. The second sheet converts these total values to values per year. This is required to do a fair comparison between the measures in the end, where the lifespan of a measure is also included. In total, each calculation sheet contains 4 'measure boxes'. This means that four different measures can be composed and compared. This is done because there are often several possible measures applicable to a damaged road surface. For the explanation of the sheets below, only measure box 1 is shown, but the explanation also applies to box 2, 3 and 4, as they are designed in the same way.

**MKI**

In figure 5 below, the calculation sheet of the total MKI value of measure 1 is shown. On the left, the user selects the demanded asphalt mixture per layer via a dropdown menu. This dropdown menu is shown in figure 4.

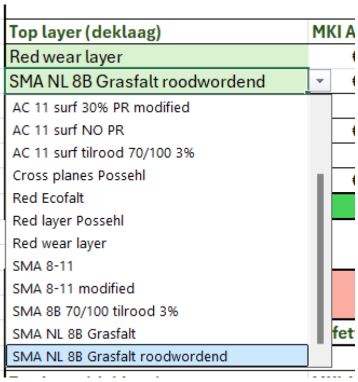


*Figure 4: Dropdown menu asphalt mixture selection*

The corresponding MKI values per module gathered in section 6.1.2 are then automatically filled in the measure box. In the column 'MKI per unit', the MKI per unit is given, which for now is the sum of modules A1-A3 and D. The number of units is received from the 'Fill-in sheet' and is used to calculate the total MKI value for each layer on the right. In the right bottom corner of the box, the total MKI of measure 1 is then given. The safety margin adds the chosen percentage extra to the final value.

| MEASURE 1 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| *Asphalt mixtures* | Safety Margin: | | 0 % | | | | | | |
| | | | | | | | | | |
| Top layer (deklaag) | MKI A1-A3 | MKI A4 | MKI A5 | MKI C1-C4 | MKI D | MKI per unit | Unit | Number of units | Total MKI top layer |
| Select | € 0.00 | € 0.00 | € 0.00 | € 0.00 | € 0.00 | € 0.00 | unit | 635 | € 0.00 |
| AC 11 surf tilrood 70/100 3% | € 16.70 | € 0.00 | € 0.00 | € 0.00 | -€ 4.37 | € 12.33 | ton | 63.5 | € 782.96 |
| Intermediate layer (tussenlaag) | | | | | | | | | Total MKI Intermediate layer |
| AC 16 bind 60% PR Lynpave | € 4.32 | € 0.00 | € 0.00 | € 0.00 | -€ 1.86 | € 2.46 | ton | 11.875 | € 29.21 |
| Base layer (onderlaag) | | | | | | | | | Total MKI base layer |
| Select | € 0.00 | € 0.00 | € 0.00 | € 0.00 | € 0.00 | € 0.00 | ton | 23.75 | € 0.00 |
| | | | | | | | | Total MKI MEASURE 1: | € 812.17 |

*Figure 5: Measure box 1 of MKI calculation sheet*

The second sheet of the MKI calculation contains the measure boxes that calculate the MKI values per year. In figure 6, this is shown for measure 1 again. By dividing the total MKI values from the sheet above by the lifespan of an asphalt mixture, the yearly MKI is calculated per measure.

| Measure 1 | | | | |
|---|---|---|---|---|
| *Asphalt mixtures* | *Type* | *Lifespan* | *Total MKI* | *Total MKI/lifespan (/year)* |
| Top layer | Select | | 0.00 | |
| Top layer | AC 11 surf tilrood 70/100 3% | 14 | 782.96 | 55.93 |
| Intermediate layer | AC 16 bind 60% PR Lynpave | 45 | 29.21 | 0.65 |
| Base layer | Select | | 0.00 | |
| | | | **Total MKI MEASURE 1:** | € 56.57 |

*Figure 6: Measure box 1 of MKI calculation sheet per year*

### $CO_2$

In figure 8 below, the calculation sheet of the total $CO_2$ emission of measure 1 is shown. In the top left, the user must select the same asphalt mixtures as in the other calculation sheets. Additionally, an asphaltset or wear layer set can be selected to perform the measure. These standard sets contain machinery and equipment used by NTP. In the bottom left, the user selects the additional machinery via a dropdown menu. Also, the transportation vehicles can be selected. These dropdown menu's are visible in figure 7.

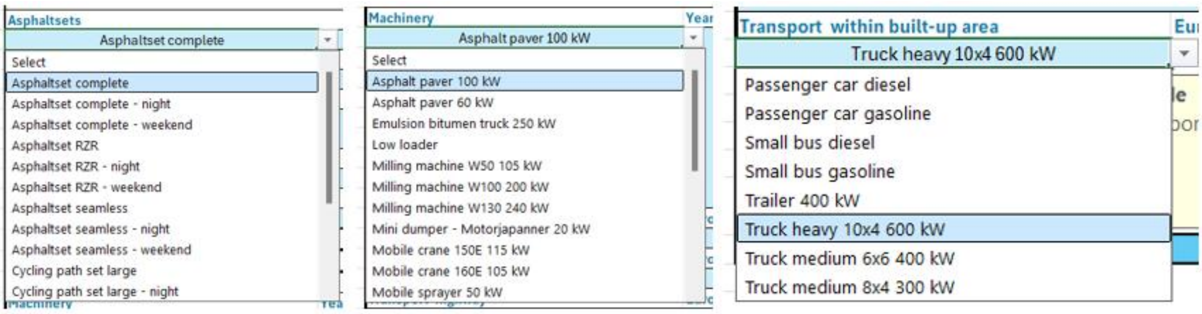


*Figure 7: Dropdown menu's machinery and transport selection*

The gathered data in chapter 6.1.3 is used here for the calculations in the measure boxes. The number of days and hours are manually set by the user, and the number of km is received from the 'Fill-in sheet'. Finally, the box calculates the total emission of the mixtures and equipment and transport.

| MEASURE 1 | | | | | |
|---|---|---|---|---|---|
| ***Asphalt mixtures*** | **Safety Margin:** | 0 % | | | |
| | | | | | |
| **Top layer (bovenlaag)** | | **Emission per ton** | **#tons (wear layer m2)** | | **Total emission asphalt layers** |
| Select | | 0 | 635 | | 0.000 ton |
| AC 11 surf tilrood 70/100 3% | | 0.12742 | 64 | | 8.155 ton |
| **Intermediate layer (tussenlaag)** | | **Emission per ton** | **#tons** | | |
| AC 16 bind 60% PR Lynpave | | 0.02688 | 12 | | 0.323 ton |
| **Base layer (onderlaag)** | | **Emission per ton** | **#tons** | | |
| Select | | 0 | 24 | | 0.000 ton |
| | | | | **Total emission mixtures:** | 8.477 ton |
| ***Asphalt equipment and transport*** | | | | | |
| | | | | | |
| **Asphaltsets** | | **Emission per day** | **Number of days** | | **Total emission asphalt sets** |
| Asphaltset complete | | 1.369 | 0.73 | | 0.999 ton |
| **Wear layer sets (excluding trucks)** | | **Emission per day** | **Number of days** | | **Total emission wear layer sets** |
| Select | | 0 | 1 | | 0.000 ton |
| **Machinery** | **Year of construction** | **Emission per hour (tons)** | **Number of hours** | | **Total emission machinery** |
| Milling machine W50 105 kW | 2019 | 0.098 | 10.1 | | 0.990 ton |
| Milling machine W130 240 kW | 2019 | 0.095 | 5.1 | | 0.485 ton |
| Spreading tractor 60 kW | 2019 | 0.014 | 16 | | 0.224 ton |
| Sweeper truck 120 kW | 2019 | 0.02 | 9.07 | | 0.181 ton |
| Surface cleaning truck 240 kW | 2019 | 0.03 | 4.06 | | 0.122 ton |
| Mobile crane 160E 115 kW | 2019 | 0.019 | 5.87 | | 0.112 ton |
| Mini dumper - Motorjapanner 20 kW | 2019 | 0.0072 | 14.7 | | 0.106 ton |
| Site hut | 2019 | 0 | 50 | | 0.000 ton |
| Select | 2019 | 0 | 0 | | 0.000 ton |
| **Transport within built-up area** | **Euro standard** | **Emission per km** | **Number of km** | **Frequency** | **Total emission transport** |
| Truck medium 6x6 400 kW | Euro 6 | 0.00078 | 100 | 1 | 0.078 ton |
| Select | Euro 6 | 0 | 0 | 1 | 0.000 ton |
| **Transport outside built-up area** | **Euro standard** | **Emission per km** | **Number of km** | **Frequency** | **Total emission transport** |
| Truck medium 6x6 400 kW | Euro 6 | 0.00057 | 200 | 1 | 0.114 ton |
| Select | Euro 6 | 0 | 0 | 1 | 0.000 ton |
| **Transport highway** | **Euro standard** | **Emission per km** | **Number of km** | **Frequency** | **Total emission transport** |
| Truck medium 6x6 400 kW | Euro 6 | 0.00094 | 400 | 1 | 0.376 ton |
| Select | Euro 6 | 0 | 0 | 1 | 0.000 ton |
| | | | | **Total emission equipment and transport** | 3.786 ton |
| | | | | **Total emission MEASURE 1:** | 12.264 ton |

*Figure 8: Measure box 1 of $CO_2$ calculation sheet*

The second sheet of the $CO_2$ calculation contains the emission per year. This sheet is shown in figure 9 below.

| Measure 1 | | | | | | |
|---|---|---|---|---|---|---|
| ***Asphalt mixtures*** | *Type* | *Lifespan* | *LCM* | *Number of replacements* | *Total emission* | *Total emission/lifespan (/year)* |
| Top layer | Select | | 630 | | 0 | |
| Top layer | AC 11 surf tilrood 70/100 3% | 14 | | 45 | 8.15488 | 0.582 |
| Intermediate layer | AC 16 bind 60% PR Lynpave | 45 | | 14 | 0.32256 | 0.007 |
| Base layer | Select | | | | 0 | |
| | | | SUM Nor: | 59 | | |
| ***Equipment and transport*** | | | | SUM E&T: | 3.78624 | |
| Top layer | | | | | | |
| Top layer | | | | 0.763 | 2.888 | 0.206 |
| Intermediate layer | | | | 0.237 | 0.898 | 0.020 |
| Base layer | | | | | | |
| | | | | | **Total emission per year MEASURE 1:** | 0.816 ton |

*Figure 9: Measure box 1 of $CO_2$ calculation sheet per year*

A measure with multiple asphalt mixtures that have different lifespans cannot be divided by one value. The layers are divided by their lifespan, but for the equipment and transport it is difficult to determine how much percentage of the emission of a machine is responsible for which layer. Therefore, the ratio between the number of replacements per layer is considered as the ratio that is used to determine the emission of the equipment and transport for each layer. This is done by calculating the least common multiple (LCM) of the lifespans. The ratio of the replacements during the LCM was used to divide the emissions from machinery and transport per layer. These emissions are then divided by the lifespan of each layer. Then, the yearly value of the asphalt mixtures, equipment, transport and asphalt sets is summed up to calculate the final value of $CO_2$ emission per year per measure.

**Costs**

In figure 10 below, the calculation sheet of the total costs of measure box 1 is shown. Just as for the $CO_2$ calculation, the user must select the same asphalt mixtures, asphalt sets, machinery, transport and now also personnel via the dropdown menu's. The gathered data in chapter 6.1.4 is used for the costs per unit. The number of units of transport is received from the 'Fill-in sheet' and from the machinery and personnel is filled in manually. Then the final costs of measure 1 are calculated in the bottom right by summing up the costs of each category.

| MEASURE 1 | | | | | |
|---|---|---|---|---|---|
| *Asphalt mixtures* | *Safety Margin:* | 0 % | | | |
| Top layer (bovenlaag) | | | | | Total costs asphalt mixtures |
| Select | € 0.00 | unit | 635 | | € 0.00 |
| AC 11 surf tilrood 70/100 3% | € 162.30 | ton | 64 | | € 10387.20 |
| Intermediate layer (tussenlaag) | | | | | |
| AC 16 bind 60% PR Lynpave | € 48.43 | ton | 12 | | € 581.16 |
| Base layer (onderlaag) | | | | | |
| Select | € 0.00 | unit | 24 | | € 0.00 |
| | | | | **Total costs mixtures:** | € 10968.36 |
| *Asphalt equipment and transport* | | | | | |
| Asphaltsets | Costs per unit | Unit | Number of units | | Total costs asphaltsets |
| Asphaltset complete | € 7675.00 | day | 0.73 | | € 5602.75 |
| Wear layer sets (excluding trucks) | | | | | Total costs wear layer sets |
| Select | € 0.00 | day | 1 | | € 0.00 |
| Machinery | Costs per unit | Unit | Number of units | Frequency | Total costs machinery |
| Milling machine W50 105 kW | € 210.00 | hour | 10.1 | 1 | € 2121.00 |
| Milling machine W130 240 kW | € 475.00 | hour | 5.1 | 1 | € 2422.50 |
| Spreading tractor 60 kW | € 60.00 | day | 2 | 1 | € 120.00 |
| Sweeper truck 120 kW | € 139.00 | hour | 9.07 | 1 | € 1260.73 |
| Surface cleaning truck 240 kW | € 209.00 | hour | 4.06 | 1 | € 848.54 |
| Mobile crane 160E 115 kW | € 79.25 | hour | 5.87 | 1 | € 465.20 |
| Mini dumper - Motorjapanner 20 kW | € 140.00 | day | 1.47 | 2 | € 411.60 |
| Site hut | € 100.00 | day | 5 | 1 | € 500.00 |
| Select | € 0.00 | unit | 0 | 1 | € 0.00 |
| Transport | Costs per unit | Unit | Number of units | Frequency | Total costs transport |
| Truck medium 6x6 400 kW | € 91.50 | hour | 9.80 | 1 | € 896.85 |
| Select | € 0.00 | hour | 0.00 | 1 | € 0.00 |
| Select | € 0.00 | hour | 0.00 | 1 | € 0.00 |
| Select | € 0.00 | hour | 0.00 | 1 | € 0.00 |
| Personnel | Costs per unit | Unit | Number of units | Frequency | Total costs personnel |
| Employee | € 55.00 | hour | 10.06 | 1 | € 553.30 |
| Select | € 0.00 | hour | 1 | 1 | € 0.00 |
| Select | € 0.00 | hour | 1 | 1 | € 0.00 |
| Select | € 0.00 | hour | 1 | 1 | € 0.00 |
| | | | | **Total costs equipment and transport:** | € 15202.46 |
| | | | | **Total costs MEASURE 1:** | € 26170.82 |

*Figure 10: Measure box 1 of costs calculation sheet*

Again, sheet 2 of the cost calculation consists of the costs per measure per year. This sheet is shown in figure 11 below. As with the annual $CO_2$ calculation sheet, the same method is applied to calculate the annual costs per measure. This includes the process of calculating the LCM, determining the replacement ratio, divide the costs according to this ratio and divide by the lifespan of each layer. The sum of the costs gives the costs per year of the measure. These yearly values are used in the TOM.

| Measure 1 | | | | | | |
|---|---|---|---|---|---|---|
| ***Asphalt mixtures*** | *Type* | *Lifespan* | *LCM* | *Number of replacements* | *Total costs* | *Total costs/lifespan (/year)* |
| Top layer | Select | | 630 | | 0 | |
| Top layer | AC 11 surf tilrood 70/100 3% | 14 | | 45 | 10387.2 | € 741.94 |
| Intermediate layer | AC 16 bind 60% PR Lynpave | 45 | | 14 | 581.16 | € 12.91 |
| Base layer | Select | | | | 0 | |
| | | | SUM: | 59 | | |
| ***Equipment and transport*** | | | | SUM E&T: | € 15202.46 | |
| Top layer | | | | | | |
| Top layer | | | | 0.763 | € 11595.10 | € 828.22 |
| Intermediate layer | | | | 0.237 | € 3607.36 | € 80.16 |
| Base layer | | | | | | |
| | | | | | **Total emission per year MEASURE 1:** | € 1663.24 |

*Figure 11: Measure box 1 of costs calculation sheet per year.*

### 6.2.6 Fill-in sheet

The purpose of the fill-in sheet is to make the tool scenario-oriented. This means that for different problems or scenarios where maintenance is required, the user can enter certain properties of, for example, the road segment to ensure that the calculations are made based on real-life data. The first part of the sheet is visible in figure 12. In this part, the user can enter some general characteristics, such as asphalt density or travel speeds, as well as the dimensions of the road segment where maintenance will take place. This road segment is again split up into the dimensions of the layer, which can be seen under 'Layer dimensions'. This way, the required number of tons of asphalt per layer is calculated, used as input for in the calculation sheets. Under 'Asphalt proceedings', the user fills in the dimensions of the road segment that needs to be removed and paved. This results in the tool calculating the total tons of asphalt that need to be transported. The average density of asphalt can be adjusted, but is set to 2.50 ton/m$^3$ for now, according to NTP. The volume of the segment can then be transformed to tons of material.

| Characteristics | Unit |
|---|---|
| *Average density asphalt:* | 2.50 (ton/m3) |
| *Average speed within built-up area:* | 40.00 (km/h) |
| *Average speed outside built-up area:* | 70.00 (km/h) |
| *Average speed highway:* | 90.00 (km/h) |

| Asphalt proceedings removing | | | | | |
|---|---|---|---|---|---|
| **Wear layer** | | | | | |
| Segment length (m) | Segment width (m) | | Segment area (m2) | Number of segments | Area wear layer (m2) |
| 0 | 0 | | 0 | 1 | 0.00 m2 |
| **Top layer** | | | | | |
| Segment length (m) | Segment width (m) | Segment height (m) | Segment volume (m3) | Number of segments | Tons in top layer |
| 635 | 1 | 0.04 | 25.4 | 1 | 63.50 ton |
| **Intermediate layer** | | | | | |
| Segment length (m) | Segment width (m) | Segment height (m) | Segment volume (m3) | Number of segments | Tons in intermediate layer |
| 95 | 1 | 0.05 | 4.75 | 1 | 11.88 ton |
| **Base layer** | | | | | |
| Segment length (m) | Segment width (m) | Segment height (m) | Segment volume (m3) | Number of segments | Tons in base layer |
| 95 | 1 | 0.1 | 9.5 | 1 | 23.75 ton |
| | | **Total m3 removed:** | **39.65** | **Total tons removed:** | **99.13 ton** |

| Asphalt proceedings paving | | | | | | |
|---|---|---|---|---|---|---|
| **Wear layer** | | | | | | |
| Segment length (m) | Segment width (m) | | Segment area (m2) | Number of segments | Area wear layer (m2) | Rounded up |
| 635 | 1 | | 635 | 1 | 635.00 m2 | 635 |
| **Top layer** | | | | | | |
| Segment length (m) | Segment width (m) | Segment height (m) | Segment volume (m3) | Number of segments | Tons in top layer | Rounded up |
| 635 | 1 | 0.04 | 25.4 | 1 | 63.50 ton | 64 |
| **Intermediate layer** | | | | | | |
| Segment length (m) | Segment width (m) | Segment height (m) | Segment volume (m3) | Number of segments | Tons in intermediate layer | Rounded up |
| 95 | 1 | 0.05 | 4.75 | 1 | 11.88 ton | 12 |
| **Base layer** | | | | | | |
| Segment length (m) | Segment width (m) | Segment height (m) | Segment volume (m3) | Number of segments | Tons in base layer | Rounded up |
| 95 | 1 | 0.1 | 9.5 | 1 | 23.75 ton | 24 |
| | | **Total m3 paved:** | **39.65** | **Total tons paved:** | **99.13 ton** | **100.00 ton** |

*Figure 12: Fill-in sheet characteristics and road segment dimensions*

Next, the transportation frequencies and distances are calculated by filling in the capacity of the trucks and the distance travelled by a vehicle within the built-up area, outside the built-up area or on the highway. This is needed for calculating the emissions based on emissions per kilometre. The red circles indicate the cells in which this can be adjusted in figure 13. These values are later used to determine the travel time of the vehicles, needed for the cost calculations. The green circles indicate how many trucks are needed based to transport all material, based on their capacity. The smaller vehicles, such as cars and buses can be filled in manually.

**Transportation frequencies**

**Removing asphalt**

| *Type of transport* | *Capacity (tons)* | *Frequency* | *Transport distance* | |
|---|---|---|---|---|
| Passenger car diesel | | 1 | Within built-up area: | 10.00 km |
| Passenger car gasoline | | 1 | Outside built-up area: | 20.00 km |
| Small bus diesel | | 1 | Highway: | 40.00 km |
| Small bus gasoline | | 1 | | |
| Trailer 400 kW | 30 | 4 | | |
| Truck heavy 10x4 600 kW | 30 | 4 | | |
| Truck medium 6x6 400 kW | 20 | 5 | | |
| Truck medium 8x4 300 kW | 20 | 5 | | |

**Paving asphalt**

| *Type of transport* | *Capacity (tons)* | *Frequency* | *Transport distance* | |
|---|---|---|---|---|
| Passenger car diesel | | 1 | Within built-up area: | 10.00 km |
| Passenger car gasoline | | 1 | Outside built-up area: | 20.00 km |
| Small bus diesel | | 1 | Highway: | 40.00 km |
| Small bus gasoline | | 1 | | |
| Trailer 400 kW | 30 | 4 | | |
| Truck heavy 10x4 600 kW | 30 | 4 | | |
| Truck medium 6x6 400 kW | 20 | 5 | | |
| Truck medium 8x4 300 kW | 20 | 5 | | |

**Transportation totals**

| *Type of transport* | *Total distance (km)* | *Within built-up area (km)* | *Outside built-up area (km)* | *Highway (km)* |
|---|---|---|---|---|
| Passenger car diesel | | 20 | 40 | 80 |
| Passenger car gasoline | | 20 | 40 | 80 |
| Small bus diesel | | 20 | 40 | 80 |
| Small bus gasoline | | 20 | 40 | 80 |
| Trailer 400 kW | | 80 | 160 | 320 |
| Truck heavy 10x4 600 kW | | 80 | 160 | 320 |
| Truck medium 6x6 400 kW | | 100 | 200 | 400 |
| Truck medium 8x4 300 kW | | 100 | 200 | 400 |

*Figure 13: Fill-in sheet transportation frequencies and travel distances*

The last part of the fill-in sheet is shown in figure 14 below. Using the average speed characteristics from the first part, the transportation time per road area is calculated per vehicle, depending on the travel distance that is filled in by the user. Finally, the tool sums up these travel times per vehicle and show the total travel time at the bottom. These values are circled in red again and are used as input for the cost calculation sheet.

| **Transportation time** | | | |
| --- | --- | --- | --- |
| **Within built-up area** | | | |
| *Type of transport* | *Average speed (km/h)* | *Distance (km)* | *Transportation time (h)* |
| Passenger car diesel | 40 | 20 | 0.50 |
| Passenger car gasoline | 40 | 20 | 0.50 |
| Small bus diesel | 40 | 20 | 0.50 |
| Small bus gasoline | 40 | 20 | 0.50 |
| Trailer 400 kW | 40 | 80 | 2.00 |
| Truck heavy 10x4 600 kW | 40 | 80 | 2.00 |
| Truck medium 6x6 400 kW | 40 | 100 | 2.50 |
| Truck medium 8x4 300 kW | 40 | 100 | 2.50 |
| **Outside built-up area** | | | |
| *Type of transport* | *Average speed (km/h)* | *Distance (km)* | *Transportation time (h)* |
| Passenger car diesel | 70 | 40 | 0.57 |
| Passenger car gasoline | 70 | 40 | 0.57 |
| Small bus diesel | 70 | 40 | 0.57 |
| Small bus gasoline | 70 | 40 | 0.57 |
| Trailer 400 kW | 70 | 160 | 2.29 |
| Truck heavy 10x4 600 kW | 70 | 160 | 2.29 |
| Truck medium 6x6 400 kW | 70 | 200 | 2.86 |
| Truck medium 8x4 300 kW | 70 | 200 | 2.86 |
| **Highway** | | | |
| *Type of transport* | Average speed (km/h) | Distance (km) | Transportation time (h) |
| Passenger car diesel | 90 | 80 | 0.89 |
| Passenger car gasoline | 90 | 80 | 0.89 |
| Small bus diesel | 90 | 80 | 0.89 |
| Small bus gasoline | 90 | 80 | 0.89 |
| Trailer 400 kW | 90 | 320 | 3.56 |
| Truck heavy 10x4 600 kW | 90 | 320 | 3.56 |
| Truck medium 6x6 400 kW | 90 | 400 | 4.44 |
| Truck medium 8x4 300 kW | 90 | 400 | 4.44 |
| **Total transportation time** | | | |
| *Type of transport* | *Total hours of all roads* | | |
| Passenger car diesel | **1.96** | | |
| Passenger car gasoline | **1.96** | | |
| Small bus diesel | **1.96** | | |
| Small bus gasoline | **1.96** | | |
| Trailer 400 kW | **7.84** | | |
| Truck heavy 10x4 600 kW | **7.84** | | |
| Truck medium 6x6 400 kW | **9.80** | | |
| Truck medium 8x4 300 kW | **9.80** | | |

*Figure 14: Fill-in sheet total transportation time*

### 6.2.7 Dashboard sheet

The dashboard sheet is the final sheet consisting of the trade-off matrices and graphs based on previous discussed sheets. The purpose of this sheet is to support the decision-making process by showing the impact on the integrated criteria of different measures. This is done by identifying the trade-offs in multiple matrices and visualize this by creating bar charts.

For the development of the dashboard, three types of TOM's are designed. Each TOM contains the quantitative and qualitative criteria that are discussed in chapter 6.2, with their values shown per measure. The first TOM shows the total values of the criteria per measure in its own unit and is shown in figure 15 below. This gives a general idea of the impact on the criteria for each measure.

| ***TOM: Final values*** | | | |
|---|---|---|---|
| **Maintenance measure** | **MKI** | **$CO_2$ emission** | **Costs** |
| ***Weights*** | *1* | *1* | *1* |
| Measure 1 | € 812.17 | 12.26 ton | € 26170.82 |
| Measure 2 | € 347.72 | 9.16 ton | € 27389.94 |
| Measure 3 | € 509.14 | 8.81 ton | € 19956.90 |
| Measure 4 | € 996.32 | 13.51 ton | € 35451.82 |

*Figure 15: Initial TOM including total output of quantitative criteria in different units*

However, these total values are not comparable because the lifespan is not included yet. Therefore, a second TOM is created where the lifespan is included, based on the annual values of the calculation sheets. This TOM is shown in figure 16.

| ***TOM: Final values per year*** | | | |
|---|---|---|---|
| **Maintenance measure** | **MKI** | **$CO_2$ emission** | **Costs** |
| ***Weights*** | *1* | *1* | *1* |
| Measure 1 | € 56.57 | 0.82 ton | € 1663.24 |
| Measure 2 | € 16.58 | 0.45 ton | € 1391.26 |
| Measure 3 | € 33.94 | 0.56 ton | € 1222.24 |
| Measure 4 | € 79.59 | 1.11 ton | € 3397.26 |

*Figure 16: Second TOM including quantitative criteria in different units per year*

This second TOM allows to compare the measures fairly per year. For example, in the initial TOM, the first or second measure look more attractive when looking at the costs. However, on annual basis, measure 3 scores better. Still, the measures can not be compared in one score, as their units are different. Therefore, a final TOM is created where the values are generalised by looking at the mutual ratio per criteria. This generalisation gives a score between 1 and 5 to each criterion for each measure. Here, 1 is the lowest (worst) score and 5 is the highest (best). Also, the qualitative criteria are added to the final TOM. The user can add a score between 1 and 5 to those criteria as well to ensure that they are integrated in the final scores as well. The final TOM is shown in figure 17 below.

| TOM: General score per year based on MAX acceptable value | | | | | | |
|---|---|---|---|---|---|---|
| Maintenance measure | MKI | $CO_2$ emission | Costs | Safety | Availability | Total weighted score |
| *Weights* | *1* | *1* | *1* | *1* | *1* | |
| Measure 1 | 2.16 | 2.07 | 3.04 | 1.60 | 2.80 | 11.67 |
| Measure 2 | 4.17 | 3.37 | 3.36 | 3.90 | 2.10 | 16.90 |
| Measure 3 | 3.29 | 2.99 | 3.56 | 3.30 | 4.40 | 17.55 |
| Measure 4 | 1.00 | 1.00 | 1.00 | 2.10 | 1.90 | 7.00 |

*Figure 17: Final design of the TOM including generalised, quantitative and qualitative criteria per year*

Based on these TOM's, multiple diagrams and charts are created to visualise the results. This allows the user to compare them even more specifically. These visualisations are shown in Appendix H.

Figures H.1, H.2 and H.3 show the total and yearly values for the MKI, costs and $CO_2$, respectively. These figures are based on the second TOM. Figure H.4 shows these values per year for each criteria in one graph, also based on the second TOM. Figure H.5 shows the final generalised scores of each measure per criteria. Figure H.6 shows the score plotted against the costs per year. In principal, the measure with the highest bar is considered the best, as it scores the highest. This final comparison generated by the tool must support the decision-making process for the municipality Enschede-Losser, aligned with their policy objectives.

## 6.4 Model verification and validation

In this chapter, the verification of the tool is performed. This process ensures that the tool has been built correctly and functions as intended. The technical correctness of the model's implementation is verified, ensuring that the conceptual design is translated correctly into a working tool. Since the tool is made in Excel, there is no extensive code script. The tool mainly consists of input and output sheets, generated by the implemented formulas. Therefore, a sensitivity analysis is an applicable verification method to find out if the formulas are entered correctly. The relationship between the input and output should be the same as in the conceptual model in section 6.2.3.

### 6.4.1 Sensitivity analysis

The sensitivity analysis will be performed for one specific sample measure. The first part of the sensitivity focuses on the 'Fill-in sheet'. This is the sheet that will be adjusted by the user every time the tool is used. Therefore, it is important that these changes are properly implemented in the tool. The properties of this measure and input parameters that will be adjusted are shown in Appendix L, table L.1. The sensitivity is done for the input parameters at 100%, 110% and 90%. The results of the criteria with the input at 100% (initial), 110% and 90% is shown in table 2 below. The change in input at each percentage is also visible in Appendix L.

*Table 2: Sensitivity analysis for MKI, $CO_2$ emission and costs using the fill-in sheet*

| Sensitivity | | | | | |
|---|---|---|---|---|---|
| **Total output** | ***(100%)*** | ***(110%)*** | **Change in output** | ***(90%)*** | **Change in output** |
| MKI (€) | 3,206.25 | 3,526.88 | 10% | 2,885.63 | -10% |
| $CO_2$ emission (ton) | 45.12 | 49.37 | 9.4% | 40.88 | -9.4% |
| Costs (€) | 107,960.71 | € 115,899.15 | 7.4% | 100,022.27 | -7.4% |
| **Annual output** | | | | | |
| MKI (€/year) | 213.34 | 234.68 | 10% | 192.01 | -10% |
| $CO_2$ emission (ton/year) | 3.45 | 3.77 | 9.3% | 3.13 | -9.3% |
| Costs (€/year) | 11,407.98 | 12,295.98 | 7.8% | 10,519.98 | -7.8% |
| **Generalised output** | | | | | |
| MKI | 2.62 | 2.62 | 0% | 2.62 | 0% |
| $CO_2$ emission | 1.25 | 1.25 | 0% | 1.25 | 0% |
| Costs | 4.72 | 4.72 | 0% | 4.72 | 0% |
| **Final output** | | | | | |
| Measure x | 14.20 | 14.20 | 0% | 14.19 | -0.07% |

The table shows that a 10% increase or decrease in input values leads to a corresponding change in total and annual outputs, while the generalised and final outputs remain unchanged. This aligns with the conceptual design, where 'Input data,' 'Total output,' and 'Annual output' are positively related, confirmed by the results. The annual output and generalised output must be negatively related. Although the generalised and annual outputs show no direct negative relationship due to proportional changes across all four measures, adjusting a measure separately does reveal this negative link. Thus, the results support the conceptual design, confirming the tool's accuracy and reliability.

The second part of the sensitivity analysis focuses on asphalt mixtures and machinery to assess whether more sustainable measures significantly impact the overall outcomes. Analysing this helps evaluate whether sustainable alternatives provide meaningful improvements. In table 3 below, the results of this part of the sensitivity analysis are shown. A sample composition is used and only the top layer is adjusted to assess the changes in total output of the criteria. Behind the output, the difference in percentage is shown. The first column includes initial values of 100%. The table shows that the criteria are positively affected by the sustainable asphalt mixtures. This could be very beneficial, as the costs are decreased while the environmental impact also decreases compared to the initial values.

*Table 3: Sensitivity analysis for different asphalt mixtures top layer*

| **Total output** | **Asphalt mixture** | *AC 11 surf tilrood 70/100 3%* | *AC 11 surf 30% PR Lynpave* | *AC 11 surf 30% PR Grasfalt* | *SMA 8B 70/100 tilrood 3%* | *SMA NL 8B Grasfalt roodwordend* |
|---|---|---|---|---|---|---|
| **MKI (€)** | | 812.2 (100%) | 370.8 (-54.3%) | 303.5 (-62.6%) | 945.5 (+16.4%) | 248.9 (-69.4%) |
| **$CO_2$ (ton)** | | 12.3 (100%) | 7.3 (-40.7%) | 4.0 (-67.5%) | 13.2 (+7.3%) | 8.1 (-34.1%) |
| **Costs (€)** | | 26,147 (100%) | 20,302 (-22.4%) | 21,417 (-18.1%) | 27,834 (+6.5%) | 26,448 (+1.2%) |

In table 4 below, a small sensitivity analysis is performed for a few types of machinery that are also part of the budget received from NTP. The composition of asphalt mixtures remains the same for each measurement, only the specific machine is adjusted. It is instantly visible that the milling machine has the most impact on the total output of the tool, while the tractor has the least impact. The tool is indeed sensitive to adjustments in asphalt mixtures, as they cause significant changes in the output. In contrast, machines result in relatively smaller changes in the total output of the criteria.

*Table 4: Sensitivity analysis for different types of machinery*

| **Total output** | **Machinery** | *Milling machine W130 240 kW* | | *Sweeper truck 120 kW* | | *Mobile crane 160E 115 kW* | | *Spreading tractor 60 kW* | |
|---|---|---|---|---|---|---|---|---|---|
| **#Hours** | | 5 | 20 | 5 | 20 | 5 | 20 | 5 | 20 |
| **$CO_2$ (ton)** | | 12.3 | 13.7 | 12.2 | 12.5 | 12.3 | 12.5 | 12.1 | 12.3 |
| ***% Change*** | | *+11.4%* | | *+2.5%* | | *+4.6%* | | *+1.7%* | |
| **Costs (€)** | | 26,099 | 33,224 | 25,581 | 27,666 | 26,077 | 27,266 | 26,080 | 26,171 |
| ***% Change*** | | *+27.3%* | | *+8.2%* | | *+4.6%* | | *+0.3%* | |

### 6.4.2 Use case: Cycle path Auke Vleerstraat Enschede

In chapter 6.4.2, a model validation method is applied to ensure the tool accurately reflects real-world scenarios and delivers reliable results. For this assignment, validation is conducted using a use case based on a current maintenance project for a cycling path at Auke Vleerstraat in Enschede. Budget data from NTP and Roelofs, including asphalt mixtures and materials, is used to test the model's ability to produce accurate outcomes. The validation focuses on asphalt paving and removal, excluding other maintenance activities like traffic control and quality assurance. Table 5 presents both the project budget inputs and the model's output.

The table shows that the costs estimated by the model are not an exact match with the real-life data, but they come close. The output of each maintenance step is approximated quite accurately. By dividing the total output of the model by the real-life output, the accuracy of the cost estimation is calculated to be 87.8%. The differences between the model and the budget plan can be explained by several factors. The input prices used in the tool are slightly outdated (2023), and machinery and equipment costs may have increased since then. Also, the model calculates transport costs based on travel time, while the budget plan includes waiting times and delays. The model assumes a standard transport distance, which can differ from the actual distances in the budget. These factors cause variations between the model's results and real-life data. Therefore, 87.8% is an acceptable percentage considering that certain parameters in the model are quite variable.

*Table 5: Real-life data compared to model estimated data*

| Asphalt removal | Real-life costs (€) | Model estimated costs (€) |
|---|---|---|
| Milling top layer | 6,426.20 | 5,830.72 |
| Milling intermediate layer | 2,492.80 | 2,148.25 |
| Asphalt paving | Real-life costs (€) | Model estimated costs (€) |
| Paving top layer | 16.846,72 | 14,943.15 |
| Paving intermediate layer | 2,658.36 | 2354.96 |
| Facilities | Real-life costs (€) | Model estimated costs (€) |
| Used facilities | 420.55 | 500.00 |
| **Total costs:** | 28,844.63 | 25,327.08 |
| **Model accuracy:** | ***87.8%*** | |

### 6.4.3 Requirements assessment

This section involves the verification and validation of the design requirements from chapter 6.2.2. A stakeholder is asked to test the tool for these requirements and validate them by giving insights into what extent the tool fulfils them. This is done by a project leader from NTP. In table 6 below it is described how the requirements are verified by the design of the tool. In addition, the insights from the stakeholder test are also visible to complete the validation part.

*Table 6: Verification and validation of design principles*

| Design principle | Verified | Validated (Stakeholder) |
|---|---|---|
| **Consistency** | - Consistent colour scheme<br>- Consistent font choice<br>- Uniform sheet layouts<br>- Consistent terminology | - 'Consistent and logical use of colours'<br>- 'Layout is clear'<br>- 'Use of relevant terminology' |
| **Transparency** | - Clear labels and sources<br>- Uniform methods and formulas<br>- Data visualisation | - 'Sources are linked to all data'<br>- 'Formulas and calculations are explained'<br>- 'Some very helpful charts are created in the dashboard' |
| **Simplicity** | - Avoid redundant elements<br>- Clear navigation<br>- Add instructions | - 'Clear navigation pane in start menu'<br>- 'Instructions to multiple cells are added'<br>- 'Simple elements and shapes are used' |
| **User friendliness** | - Clear navigation<br>- Simple language<br>- Organised design/interface<br>- Provide manual<br>- High accessibility | - 'Navigation is enhanced by included manual'<br>- 'Sheet names are self explainable'<br>- 'Clear design of calculation sheets allowing the user to fill-in easily' |
| **Flexibility** | - Include weight options<br>- Provide room for extension<br>- Data can be updated<br>- Multiple language support | - 'Weights can be easily adjusted'<br>- 'Criteria names can be adjusted, providing room for expansion and adaptability'<br>- 'New data from 2025 can be put in the tool'<br>- 'The tool is developed in Dutch as well as in English' |

From the table, the stakeholder confirms that the design principles have been effectively implemented in the tool. In addition, some points of improvement were mentioned as well to integrate the principles even better (mainly for user-friendliness):

- Add option to use different asphalt colours in a single measure
- Add option to enter different surface ($m^2$) of wear layer in a single measure
- Add a few processes that automate the fill-in process
- Lock cells that should not be modified by the user

This improves the user friendliness and flexibility for project-specific requirements.

## 6.5 Model application

This chapter compares the output provided by the model for the use case with two other measures. In this way, a brief analysis can be conducted to provide insight into the impact of the budget from NTP in relation to other measures. The sensitivity analysis revealed that asphalt mixtures have the greatest impact on the output of a measure. Therefore, adjustments will be made to the selected asphalt mixtures for the two other measures. The machines and transport vehicles will not be adjusted, they are the same as in the budget. Measure 2 features a black top layer instead of red, Measure 3 includes a sustainable top layer, and Measure 4 has an additional base layer. This is to assess the impact of colour and sustainability. The results and selected mixtures for the different variants are shown in table 7.

*Table 7: Comparing different measures to the budget measure from NTP*

| ***Measure →*** | **Measure 1 (Use case)** | **Measure 2 (Black surface)** | **Measure 3 (Sustainable)** | **Measure 4 (Base layer)** |
|---|---|---|---|---|
| ***Asphalt mixture per layer ↓*** | | | | |
| **Wear layer** | - | - | - | - |
| **Top layer** | AC 11 surf tilrood 70/100 3% | AC 11 surf 30% PR | AC 11 surf 30% PR Grasfalt | AC 11 surf tilrood 70/100 3% |
| **Intermediate layer** | AC 16 bind 60% PR Lynpave | AC 16 bind 60% PR Lynpave | AC 16 bind 60% PR Lynpave | AC 16 bind 60% PR Lynpave |
| **Base layer** | - | - | - | AC 16 base 50% PR modified |
| ***Output:*** | | | | |
| **Total MKI (€)** | 812.17 | 488.95 | 303.53 | 910.97 |
| **MKI per year (€)** | 56.57 | 33.49 | 20.24 | 58.77 |
| **Total $CO_2$ (ton)** | 12.26 | 8.59 | 6.77 | 13.36 |
| **$CO_2$ per year (ton)** | 0.82 | 0.55 | 0.42 | 0.81 |
| **Total costs (€)** | 26,171 | 20,201 | 21,441 | 27,333 |
| **Costs per year (€)** | 1,663 | 1,237 | 1,325 | 1,580 |

Visualising the output with the tool results in the chart in figure 18 below (received from the Dutch version of the tool). To eliminate subjective impact, a score of 2 out of 5 has been assigned to safety and accessibility for all measures.

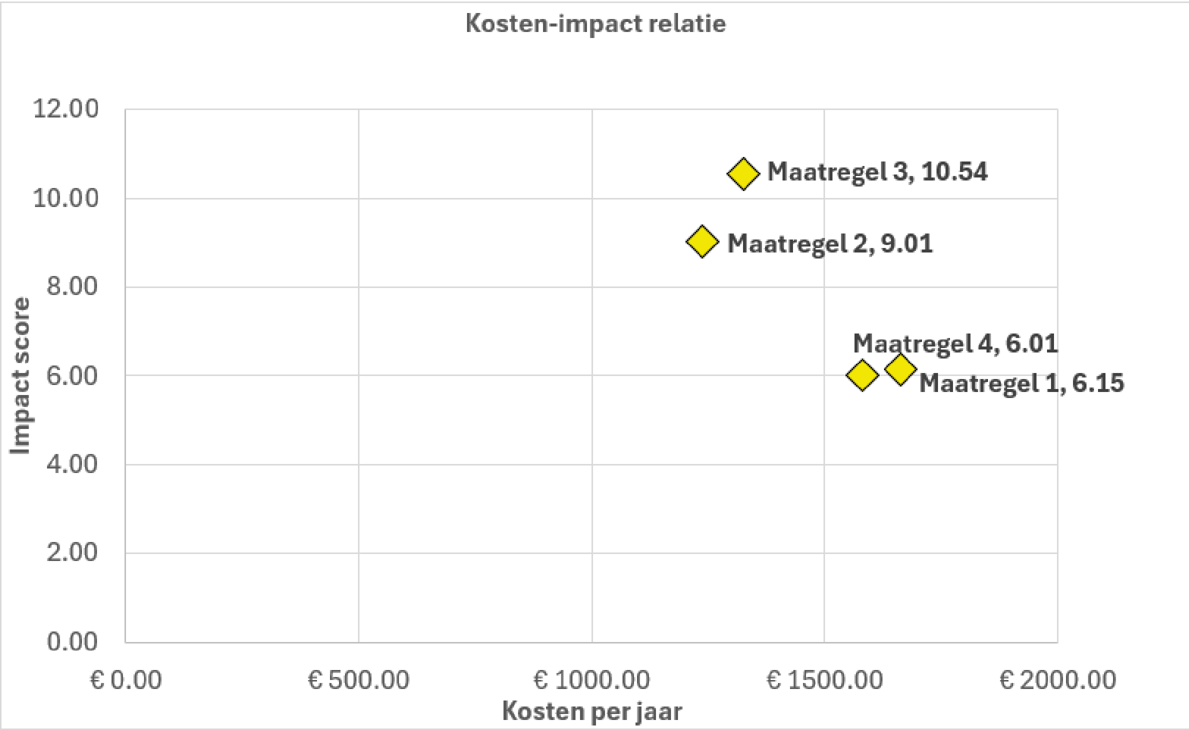


*Figure 18: Cost-impact relationship of budget and sample measures*

The table shows that the use of sustainable asphalt (measure 3) has the lowest total MKI and total $CO_2$ emissions. The sustainable mixture significantly reduces environmental impact. The black surface (measure 2) also reduces environmental impact, a bit less significant. However, it is a bit less expensive than the sustainable option. Adding a base layer (measure 4) does increase the total output of each criterion, except for the costs per year.

The figure shows that measure 1 and 4 are not cost-efficient. This is because measure 2 and 3 have higher scores and lower annual costs. In addition, a small increase in annual costs results in a relatively large improvement in the score for measure 3 compared to measure 2. The tool suggests that the budget from the use case has room for improvement in material selection and reveals that more expensive can result in both higher and lower scores of a measure. These insights must be considered during the decision-making process.

# 7. Discussion

This chapter will discuss the methodology and findings provided by the tool. First, some limitations of the methodology are discussed, followed by the model limitations. Finally, it is reflected on how the tool helps in the asphalt maintenance decision-making.

## 7.1 Methodological limitations

Methodological choices can impact the tool's development. Data for the tool was mainly sourced from NTP and Roelofs, making it dependent on external data. Values like MKI and CO2 emissions rely on complex calculations, and different parties may use varying methods to gather this data, potentially influencing both the input and output of the model. Furthermore, only data for modules A1-A3 and D has been fully provided, with A4, A5, B, and C missing. If these modules are added in the future, the model's output will change.

Additionally, data comes from various sources, including companies, suppliers, machinery, and asphalt mixtures. Since different projects involve different companies and suppliers, the data used here may not fully represent real-life projects, affecting accuracy. The tool may not be representative of all maintenance techniques, as various mixtures and machines are used by different companies. $CO_2$ emissions data for transport and machinery is derived from the TNO tool, and incomplete data can lead to varying outputs.

Also, collecting documents with data means that they may become outdated or change in the future. Also, for some prices of asphalt mixtures and machinery, price indications have been used instead of the exact prices. For example, the hourly and daily rates of many machines come from documents created in 2023. The current prices can therefore be different. However, in the datasheets, the user can easily change the prices or MKI values, to keep the tool up to date in the future.

The sensitivity analysis mainly verifies if formulas and relationships are implemented correctly, but underlying assumptions or extreme conditions are harder to verify due to the lack of a 'correct' model for comparison. In addition to formula verification, a model validation method was used to assess whether the tool generates realistic data. While the model's accuracy is relatively high, it relies on data from only one real-life project, introducing some uncertainty. The tool could be further validated with additional empirical data or use cases. Additionally, the use case only includes budget values for asphalt mixtures, equipment, and transport, excluding costs for road closures, reinforcement, etc., meaning actual costs are higher than what the tool shows. However, this is not an issue for comparison purposes, as the relative differences between maintenance measures can still be consistently evaluated.

Another limitation is that the design principles were validated by a single stakeholder. This means that the assessment of the implementation of these requirements was based on the perspective of one person, which could lead to a different conclusion than if multiple stakeholders had been involved.

## 7.2 Tool limitations

As a result of the choices in the methodology, the tool also has a number of limitations.

Firstly, the tool is limited in calculating the exact MKI and $CO_2$ values for the entire lifespan of a maintenance measure. As mentioned above, some values for specific modules are not available yet. This decreases the capacity of the tool to do complete estimations of these criteria.

Secondly, the methodology integrates three quantitative and two qualitative criteria, giving the tool a significant impact on asphalt maintenance decision-making. However, it may be slightly incomplete for certain projects, as other criteria could be relevant depending on the user's priorities and the project's location.

The tool has some limitations due to certain assumptions and simplifications. It assumes a standardized maintenance process, while in reality, this can vary by project. For example, environmental factors like bad weather can extend maintenance periods. Additionally, some parameters, such as emission factors, MKI values, and asphalt mixture lifespans, are assumed to be constant, even though they may differ depending on factors like road density or technical developments at each location. For simplicity, the tool also excludes certain processes, such as traffic diversions, road closures, and asphalt reinforcement. These exclusions can impact the overall output of a maintenance measure.

Another important assumption in the tool is related to converting total output of a criterion to output per year. It is not possible to divide a measure by just one lifespan, as the layers consist of different lifespans. Therefore, the total $CO_2$ emissions and costs are partly converted to a value per year using a ratio. This ratio is based on the number of replacements per layer within a certain period of time. The more often a layer is replaced, the more emissions and costs are incurred due to increased material and energy consumption. This ratio limits the accuracy of the tool.

## 7.3 Tool evaluation and reflection

The performance and use of the tool identify multiple strengths and weaknesses. A major strength of the tool is that the design principles have been well integrated, validated in section 6.4.3. The use of clear labels, colour coding, uniform methods and formulas and instructions contributes to the tool's strong consistency and transparency. The provided manual makes the tool accessible to multiple users ensuring that the tool is easy to navigate. The visualisation of results facilitates the interpretation of the output. This enhances the simplicity and user-friendliness of the tool. The user can compile up to 4 different measures, which are scenario-oriented. Weighting options are included and there is room for extension. This ensures high flexibility of the tool.

On the other hand, some weaknesses must be acknowledged as well. First, the tool relies on several assumptions, such as equal asphalt lifespans and fuel consumption of machinery. These assumptions might deviate from real-world conditions, affecting the accuracy of the results. This inaccuracy is also affected by the limited model validation. Also, most of the model input is entered manually. This also applies to the composition of the measures. This can be error-prone if the user enters the data incorrectly. Lastly, while the tool demonstrated good performance in the scenario of the model validation, its applicability to other projects or regions remains uncertain, as it is not further tested yet.

The tool improves the asphalt maintenance decision-making in multiple ways. First of all, by optimising the material selection. The tool helps identify which maintenance measures provide the best balance between cost, sustainability, and performance (decision criteria). This balance is numerically substantiated by the tool. Secondly, the tool helps with reducing the environmental impact of a measure. By quantifying $CO_2$ emissions and MKI, more sustainable choices can be made. The tool also supports strategic planning by identifying the impact of a measure per year on different criteria. To achieve policy goals, the annual environmental impact can be considered to align the maintenance strategies with the objectives. Additionally, the tool allows users to quickly analyse different maintenance scenarios, clearly showing their impact on costs and sustainability, thereby improving the time management aspect of decision-making.

Considering that there are many advanced methods available, such as Life Cycle Assessment (LCA) and AI-driven models (literature study section 5.2 and 5.4), the tool offers a simpler, more accessible approach to asphalt maintenance decisions. While it may not provide the same level of detail as these advanced methods, it’s a practical solution for users who need quick, clear insights without needing deep technical knowledge. It balances ease of use with reliable data. This makes it a good option for various stakeholders.

# 8. Conclusion

The main objective of this research is to design a tool that identifies the impact on MKI, $CO_2$ emissions and costs per asphalt mixture or maintenance measure. By integrating the decision-criteria per measure into a trade-off matrix (TOM), the decision-making process can be measurably substantiated and contribute to achieving the policy objectives from the municipality Enschede-Losser. This chapter will answer the two research questions.

***Main research question 1: What are the MKI, $CO_2$ emissions and costs of asphalt mixtures and maintenance measures during their life-cycle phases?***
NTP and Roelofs use both traditional and sustainable asphalt mixtures, with AC 11 Surf and SMA being the most common. They use standard asphalt sets, which include machinery, transport vehicles, and personnel. The MKI and CO2 values are gathered per asphalt mixture, with modules A1-A3 and D fully available, but A4, A5, B, and C data are not yet complete. Sustainable asphalt mixtures generally show a lower MKI and CO2 value per ton compared to traditional mixtures.

Costs are also gathered per asphalt mixture, with sustainable mixtures not always being more expensive than traditional ones. The cost of machines and personnel can vary greatly depending on their function within the maintenance project.

From this, it can be concluded that different mixtures, machines, and transport vehicles have varying impacts on the total output of the criteria. Sustainable asphalt is generally better for minimizing environmental impact compared to traditional asphalt, due to its comparable lifespan. Furthermore, sustainable asphalt does not always result in higher costs. In conclusion, understanding the differences in MKI, CO2 emissions, and costs between sustainable and traditional asphalt is critical for designing the tool and making informed decisions about asphalt maintenance measures.

***Main research question 2: How can MKI, CO2 emissions, and costs be integrated into a trade-off matrix to assess asphalt maintenance measures?***
Integrating both quantitative and qualitative criteria is key to the TOM tool's ability to support decision-making in asphalt maintenance. Quantitative criteria such as MKI, $CO_2$ emissions, and costs are based on real-world data, providing clear outputs that allow for proper assessment of environmental and financial impacts. Qualitative criteria, like safety and availability, add a subjective aspect to the decision-making process, ensuring that other project (or user) priorities are considered as well. The tool is also flexible, letting users add extra criteria depending on the specific project needs.

Five design principles are used to support the integration of the criteria, enhancing the usability of the tool. These are consistency, transparency, simplicity, user friendliness and flexibility. The principles provide a clear framework for how the criteria must be presented and interpreted. Based on the stakeholder validation, it can be concluded that the principles are integrated well in the design. The conceptual model also plays an important role, clearly showing the relationships between the different criteria and outlining how data flows between the sub-models. This is considered in the design of the tool, making sure the criteria are integrated effectively.

Besides fulfilling the design requirements, the criteria are also integrated in a comparable way to ensure proper visualisation. Therefore, the total output of the criteria is converted to an annual value. These annual values can be summed per measure by generalising the scale between 1 and 5 to generate total scores. These total scores per measure are visualised to allow for quick and fair comparison.

Lastly, the criteria integration requires model verification and validation, making sure the formulas are correctly implemented, and the tool is accurate. This ensures the criteria are properly represented and function as expected. Ultimately, the integration of both quantitative and qualitative criteria into the TOM tool, supported by model verification and validation, ensures that decision-makers have a reliable tool to assess the full impact of asphalt maintenance measures.

# 9. Recommendations

Multiple recommendations can be made regarding the results and working of the tool. Also, recommendations regarding future research on the development of the tool can be made to create even more reliable and accurate results.

## 9.1 Tool application

The tool generates multiple scenarios in which it is beneficial for both the costs and environmental impact to use sustainable asphalt mixtures. Therefore, it is strongly recommended to invest in the development of these mixtures to contribute positively to achieving the policy goals for 2025 and 2050. Also, in the decision-making process, it is recommended to consider long-term cost efficiency. Although some maintenance measures may have higher initial costs, the model shows that they can lead to lower annual costs over time.

For the application of the tool, it is recommended to put different budget scenarios in the tool for various projects. This allows the user to quickly find out what the financial feasibility and environmental impact is of a project. By adjusting the type of asphalt mixture or the transport type, one can quickly compare the impact of each measure. This enhances the decision-making process by identifying potential cost-saving opportunities.

To ensure the tool remains accurate and relevant, the input data must be regularly updated regarding costs, $CO_2$ emission and MKI values. This ensures that the tool remains accurate and relevant. Especially, since machinery prices change almost every year and new technological developments cause maintenance processes to become more environmentally friendly. As mentioned in the discussion in section 7.1, requesting data from more companies could result in more accurate input of the model, optimizing the output of the tool as well.

## 9.2 Future research

For the completeness of the tool, it is recommended to add the missing data from modules A4, A5, B and C as quickly as possible. This increases the accuracy and reliability of the tool, since the uncertainty of missing data is decreased. Also, by integrating additional quantitative and qualitative criteria, the tool supports the decision-making process more comprehensive.

To further verify and validate the tool, several actions can be carried out. Based on these, the tool can be improved to enhance its accuracy and reliability. The limitations in section 7.1 can be minimized through future research. Verification requires additional testing to ensure the correctness of formulas and calculations across multiple scenarios. Extra variables and conditions can also be tested for complete verification. For validation, multiple real-life project data can be filled-in of which the outcome is compared to actual measured data. Furthermore, the tool can be compared to other impact calculation tools within asphalt maintenance. In addition to chapter 6.5, more stakeholders can be asked to test the tool in order to validate the implementation of the design principles.

As discussed in section 7.2 and 7.3, the annual output is calculated based on a certain ratio, causing small uncertainty in the model. This ratio can be transformed into actual measured values per road layer in the future by expanding the tool, offering room to calculate actual data instead of assuming a ratio.

# 10. References

Asfaltfrezen Asfaltmachine Bomag Bekijk het aanbod bij Kemp Groep. (2025). *Kemp Groep*. https://kemp-groep.nl/machines-kemp-groep/bomag-asfaltfrezen#form

AsfaltNu (2024). *SMA, met grote vormvastheid.* AsfaltNu. https://www.asfaltnu.nl/asfaltsoorten/sma

Asphalt paver, used asphalt paver for sale. (2024). *Machineryline.* https://machineryline.info/-/asphalt-pavers--c126

Bak, I., Overmars, L., Van Der Kruk, T., Ecochain, & TNO. (2022). *LCA Achtergrondrapport voor Nederlandse Branchereferentiemengsels 2022.* Ecochain. https://media.umbraco.io/bouwend-nederland/05mnrwao/20220331_lca-achtergrondrapport-voor-nederlandse-branchereferentiemengsels_definitief.pdf

Bandenwals Bomag Bekijk het assortiment. (2024, July 25). *Kemp Groep.* https://kemp-groep.nl/machines-kemp-groep/bomag-bandenwalsen

Burningham, S., & Stankevich, N. (2005). *Why road maintenance is important and how to get it done*. The World Bank. https://trid.trb.org/View/759195

Dynapac. (2025). *CA302D*. Dynapac. https://dynapac.com/en/products/compaction/ca302d

DAF CF85 EURO 5 Emulsie spuitwagen bitumen sprayer. (2024). *Machineryline.* https://machineryline.nl/-/verkoop/bitumen-sprayers/DAF/CF85-EURO-5-Emulsie-spuitwagen--22032219222872244500

Deng, X., Cheng, P. (2002). Calculation of contaminant concentrations and required air volume for roadway tunnel with longitudinal ventilation system. *China Journal of Highway and Transport*, 86-88.

Haider, S. W., & Dwaikat, M. B. (2011). Estimating optimum timing for preventive maintenance treatment to mitigate pavement roughness. *Transportation Research Record Journal of the Transportation Research Board*, *2235*(1), 43–53. https://doi.org/10.3141/2235-06

Han, C., Ma, T., & Chen, S. (2021). Asphalt pavement maintenance plans intelligent decision model based on reinforcement learning algorithm. *Construction and Building Materials*, *299*, https://doi.org/10.1016/j.conbuildmat.2021.124278

Hillege, A. L. (2024, July 31). *Milieukostenindicator (MKI) - Overzicht - Ecochain - LCA software company*. Ecochain. https://ecochain.com/nl/blog/milieukosten-indicator-mki/

Huang, J., Han, C., Wei, W., & Zhao, C. (2023). Analysis of long-term maintenance decision for asphalt pavement based on analytic hierarchy process and network level optimization decision. *Electronic Research Archive*, *31*(9), 5894–5916. https://doi.org/10.3934/era.2023299

Huang, Y., Bird, R., Heidrich, O. (2009, January). Development of a life cycle assessment tool for construction and maintenance of asphalt pavements, *Journal of Cleaner Production*, https://doi.org/10.1016/j.jclepro.2008.06.005 283-296

Impacts, E. (2004). Fuel Efficiency of Road Pavements. *Joint EAPA and Eurobitume Task Group on Fuel Efficiency, Industry Report. European Asphalt Pavement Association, Brussels, Belgium.*
Inter-Techno. (2024). *Weycor AW 260 Wals | Robuust en Efficiënt - Inter-Techno*. https://intertechno.nl/product/weycor-aw260/

Jiang, R., Wu, C., Song, Y., Wu, P. (2020, December 20). Estimating carbon emissions from road use, maintenance and rehabilitation through a hybrid life cycle assessment approach – A case study. *Journal of Cleaner Production.* https://doi.org/10.1016/j.jclepro.2020.123276

Johnson, P.E. (2000, February). BEST PRACTICES HANDBOOK ON ASPHALT PAVEMENT MAINTENANCE. *University of Minnesota Center for Transportation Studies*. https://pages.mtu.edu/~balkire/CE5403/AsphaltPaveMaint.pdf, 4-8

Johnston CX400 road sweeper, used Johnston CX400 road sweeper for sale. (2024). *Autoline.* https://autoline.info/-/road-sweepers/Johnston/CX400--c336tm3035m41833

Kennisnet, G. (2025). *Groen kennisnet*. https://groenkennisnet.nl/nieuwsitem/trekkergewicht-en-vermogen-1

Lectura. (2024). *Volvo L70H specificaties & technische gegevens*. Lectura-specs. https://www.lectura-specs.nl/nl/model/bouwmachines/wielladers-volvo/l70h-11683508

Lectura. (2024). *Volvo L90H specificaties & technische gegevens*. Lectura-specs. https://www.lectura-specs.nl/nl/model/bouwmachines/wielladers-volvo/l90h-11683509

Lee, H. H. Y. & Scott, D. (2009). Overview of maintenance strategy, acceptable maintenance standard and resources from a building maintenance operation perspective. *Journal of Building Appraisal*, 269-278, https://doi.org/10.1057/jba.2008.46

Li, F., Feng, J., Li, Y., Zhou, S. (2021) Preventive Maintenance Technology for Asphalt Pavement. *Springer Nature*. https://link.springer.com/book/10.1007/978-981-15-6206-8

Li, J., Yin, G., Wang, X., & Yan, W. (2021). Automated decision making in highway pavement preventive maintenance based on deep learning. *Automation in Construction*, *135*, 104111. https://doi.org/10.1016/j.autcon.2021.104111

Liu, X., Yu, H., Miao, H. (2018, February 6). Preventive Maintenance Decision Making of Asphalt Pavement Based on Fuzzy Comprehensive Evaluation Method. *ASCE*. https://ascelibrary.org/doi/abs/10.1061/9780784481240.028

Machines - Nido. (2017, December 19). *Nido*. https://www.nido.be/machines/

Marovic, I., Androjic, I., Jajak, N., & Hanak, T. (2018, May 29). Urban Road Infrastructure Maintenance Planning with Application of Neural Networks. *Wiley.* https://doi.org/10.1155/2018/5160417

Municipality of Enschede-Losser. (2023, November 29). *'Meerjarige programmatische aanpak Groot Onderhoud Asfaltwegen gemeente Enschede en gemeente Losser' (2nd version).*

NTP. (2024, September 10). *Lynpave Asfalt Specialist | Expertise en Snelle Respons!*. NTP. https://ntp.nl/duurzaamheid/lynpave-asfalt/

Ollila, A. & Malmipuro, M. (1999). Maintenance has a role in quality. *The TQM Magazine,* 17-21.
Pamuković, J. K., Rogulj, K., Dumanić, D., & Jajac, N. (2020). A sustainable approach for the maintenance of asphalt pavement construction. *Sustainability*, *13*(1), 109. https://doi.org/10.3390/su13010109

Peng, B., Cai, C., Yin, G., Li, W., Zhan, Y. (2015, April). Evaluation system for CO2 emission of hot asphalt mixture. *KeAi.* https://doi.org/10.1016/j.jtte.2015.02.005

Qiao, Y., Wen, X., Liu, S., Lv, S., He, L. (2025, January). Stochastic analysis for comparing life cycle carbon emissions of hot and cold mix asphalt pavement systems. *Elsevier.* https://doi.org/10.1016/j.resconrec.2024.107881

Rani, N., Baharum, M., Akbar, A. & Nawawi, A. (2015). Perception of Maintenance Management Strategy on Healthcare Facilities. *Procedia – Social and Behavioral Sciences*, 272-281, https://doi.org/10.1016/j.sbspro.2015.01.037

Rijkswaterstaat. (2022, April). Verificatie Geschiktheid Wegenbouwmaterialen en - technieken (VGW). *Rijkswaterstaat.* https://techniekacademie.rijkswaterstaat.nl

RockAsphalt. (2023, December 1). The evolving world of asphalt maintenance – Rockasphalt.com. *Rock Asphalt*. https://rockasphalt.com/the-evolving-world-of-asphalt-maintenance/

Roggeveen, P. (2023, July 27). Waarom is duurzaamheid vaak zo duur?. *WEAR*. https://wear-store.nl/blogs/nieuws/waarom-is-duurzaamheid-vaak-zo-duur#:~:text=Onderzoek%20en%20Ontwikkeling%3A%20Een%20belangrijke,nieuwe%20technologie%C3%ABn%2C%20materialen%20en%20productiemethoden

Ruiz, A., Kruijf, J. V., Santos, J., Keijzer, E., Volker, L., & Dorée, A. (2024). The slow implementation of sustainable innovations in the asphalt paving sector: the role of actors and their interactions. *Construction Management and Economics*, 902–925, https://doi.org/10.1080/01446193.2024.2360992

Santos, J., Ferreira, A., Flintsch, Gerardo. (2014, August 13). A life cycle assessment model for pavement management: road pavement construction and management in Portugal. *tandfonline.* https://www.tandfonline.com/doi/abs/10.1080/10298436.2014.942862

Shafiee, M. & Sørensen, J. D. (2017). Maintenance optimization and inspection planning of wind energy assets: Models, methods and strategies. *Reliability Engineering and System Safety*, 1-19 https://doi.org/10.1016/j.ress.2017.10.025

Shin, J. H. and Jun, H. B. (2015). On condition based maintenance policy. *Journal of Computational Design and Engineering*, 119-127, https://doi.org/10.1016/j.jcde.2014.12.006

Stenström, C., Norrbin, P., Parida, A., & Kumar, U. (2015). Preventive and corrective maintenance – cost comparison and cost–benefit analysis. *Structure and Infrastructure Engineering*, 603–617, https://doi.org/10.1080/15732479.2015.1032983

Suwarto, F., Parry, T., & Airey, G. (2023). Review of methodology for life cycle assessment and life cycle cost analysis of asphalt pavements. *Road Materials and Pavement Design*, *25*(8), 1631–1657. https://doi.org/10.1080/14680629.2023.2278149

TNO. (2025). *Bouw emissie tool.* TNO. https://www.bouwemissies.nl/

Vaitkus, A., Cygas, D., Motiejunas, A., Pakalnis, A., Miskinis, D. (2016). IMPROVEMENT OF ROAD PAVEMENT MAINTENANCE MODELS AND TECHNOLOGIES. *THE BALTIC JOURNAL OF ROAD AND BRIDGE ENGINEERING,* 242-249, https://bjrbe-journals.rtu.lv/bjrbe/article/view/bjrbe.2016.28/372

Velmurugan, R. S. & Dhingra, T. (2015). Maintenance strategy selection and its impact in maintenance function: A conceptual framework. *International Journal of Operations and Production Management*, 1622-1661, https://doi.org/10.1108/IJOPM-01-2014-0028

VOLVO EW160E. (2025). *SMT.* https://www.smt.network/netherlands/nl/machines-uitrustingsstukken/nieuwe-machines/ew160e/

VOLVO EW150E. (2025). *SMT.* https://www.smt.network/netherlands/nl/machines-uitrustingsstukken/nieuwe-machines/ewr150e/

Warm Mix Asphalt - EAPA. (2022, April 28). *EAPA*. https://eapa.org/warm-mix-asphalt/

Wat is Ecofalt? - Ecofalt. (2023, July 5). *Ecofalt*. https://www.ecofalt.nl/watisecofalt/

What is Sustainability? (2024). *UCLA*. https://www.sustain.ucla.edu/what-is-sustainability/

Xu, B., Li, M., Liu, S., Fang, J., Ding, R., Cao, D. (2018, December 10). Performance analysis of different type preventive maintenance materials for porous asphalt based on high viscosity modified asphalt. *Elsevier.* https://doi.org/10.1016/j.conbuildmat.2018.10.004

Xu, X., Wang, S., Kang, F., Li, S., Li, Q., Wu, T. (2022, March 27). Multi-Attribute Decision-Making Method in Preventive Maintenance of Asphalt Pavement Based on Optimized Triangular Fuzzy Number. *Construction and Building Materials,* 320-329*,* https://doi.org/10.3390/su16072787

Yu, B., Wang, S., Gu, X. (2018, July 10). Estimation and uncertainty analysis of energy consumption and CO2 emission of asphalt pavement maintenance. *Elsevier* https://doi.org/10.1016/j.jclepro.2018.04.068

Zaniewski, J., Mamlouk, M. (1996, February) Pavement Maintenance Effectiveness - Preventive Maintenance Treatments. *Journal of Cleaner Production,* 326-333*,* https://www.fhwa.dot.gov/pavement/pubs/013734.pdf

# 11. APPENDIX

## APPENDIX A

Vraagdocument – 'Groot Onderhoud Asfaltwegen' gemeente Enschede en gemeente Losser

### 1. Inleiding

Gemeente Enschede en gemeente Losser willen de komende jaren de focus leggen op het behalen van de doelstellingen die zij hebben ten aanzien van klimaat, milieu en natuur. Beide gemeenten hebben eigen organisatiedoelstellingen, die deels zijn afgeleid van de landelijke doelstellingen voor 2030 en 2050 op deze thema's.

Naast de landelijke doelstellingen is er gekeken naar de eigen beleidsdoelstellingen van zowel gemeente Enschede als Losser. Van daaruit hebben gemeente Enschede en Losser samen de voor dit programma relevante doelstellingen vastgesteld. In het hoofdstuk 'Doelstellingen en ambities' zijn deze doelstellingen beschreven. Op basis van deze gedeelde beleidsdoelstellingen zijn programma doelstellingen opgesteld. Daarnaast zijn er een aantal randvoorwaarden die beide gemeenten stellen voor dit programma. Ook deze zijn in het volgende hoofdstuk beschreven.

De overheid kan en moet een belangrijke aanjager van vernieuwing zijn. Vooral voor de infrasector die gekenmerkt wordt door het feit dat deze maar één klanttype heeft, namelijk de overheid. Daarbij geldt de stelling dat 'Als overheden doen wat nodig is, gaat de markt doen wat mogelijk is'. Daarmee bedoelen we dat als de overheid de omstandigheden creëert en de ruimte geeft om te ontwikkelen, deze ontwikkelingen in de markt op gang zullen komen.

De komende jaren moeten diverse innovaties plaats vinden om de landelijke, gemeentelijke en de programma doelstellingen te behalen. Daarbij kan onderscheid gemaakt worden tussen productinnovaties, procesinnovaties, economische en sociale innovatie.

Om de doelstellingen van 2030 en 2050 te kunnen bereiken, moeten opdrachtgever (overheid) en opdrachtnemer (markt) meer en beter gaan samenwerken. De huidige manier van aanbesteden zorgt ervoor dat de samenwerkingen, vanwege de projectmatige aanpak, te kort-cyclisch zijn. Dit is de reden dat gekozen wordt voor een meerjarige programmatische aanpak.

Gemeente Enschede en gemeente Losser willen de komende jaren samen optrekken voor het onderhoud en het aanjagen van ontwikkelingen. Een van de eerste opgaves waar dit wordt gehanteerd is dit programma met betrekking tot het asfaltonderhoud.

Dit vraagdocument is een dynamisch document dat in de loop van het proces richting opdrachtverstrekking continu wordt aangevuld en up-to-date gehouden.

Vraagdocument – 'Groot Onderhoud Asfaltwegen' gemeente Enschede en gemeente Losser

### 2. Doelstellingen en ambities

De eerder beleidsdoelstellingen en ambities van beide gemeenten zijn het vertrekpunt voor dit programma en vormen de basis voor de selectie- en gunningscriteria. In dit hoofdstuk wordt nader ingegaan op deze doelstellingen en ambities.

#### 2.1 Beleidsdoelstellingen

Gemeenten staan de komende jaren voor grote uitdagingen. Voor een deel van deze uitdagingen zijn landelijk doelstellingen bepaald, bijvoorbeeld ten aanzien van klimaatneutraliteit en circulariteit. Daarnaast hebben gemeenten hun eigen beleidsdoelstellingen waarop wordt gestuurd en bestuurd. De volgende, voor dit programma relevante beleidsdoelstellingen van gemeente Enschede en Losser liggen ten grondslag aan dit programma:

- Integrale ontwikkeling
- $CO_2$-neutraal in 2050 (en 50% in 2030)
- Gezonde leefomgeving
- Klimaatadaptieve leefomgeving
- Circulair in 2050 (en 50% in 2030)

#### 2.2 Programma doelstellingen en ambities

Deze beleidsdoelstellingen van beide gemeenten zijn zo SMART[1] mogelijk vertaald naar ambities en doelstellingen voor het programma asfaltonderhoud. Daarbij is de vraag gesteld: wat willen beide gemeenten na afloop van het programma concreet hebben bereikt? Daar zijn de volgende specifieke doelstellingen/ambities uit voortgekomen:

- Ontwikkelen is integraal onderdeel van het voorbereidingsproces
- De organisatie stuurt op integraliteit met de opgaven (klimaat, milieu, grondstoffen)
- Meer continuïteit, uniformiteit in het proces, betere spreiding budgetten en 50% lagere transactiekosten
- $CO_2$ neutraal door toepassing producten waarmee de uitstoot van $CO_2$ met tenminste 50% wordt verminderd
- Proces waarmee op de bouwplaats uitstoot volledig wordt vermeden
- Geen toepassing van producten die bij de productie en/of verwerking toxische stoffen uitstoten (b.v. stikstof, fijnstof, benzeen)
- De activiteiten dragen altijd bij aan een gezondere leefomgeving
- De activiteiten dragen altijd bij aan een klimaatadaptieve leefomgeving.
- Er worden geen primaire abiotische grondstoffen meer toegepast
- Tenminste 50% van de verwerkte producten en materialen uit abiotische grondstoffen worden oneindig in de waardeketen behouden, door ze te hergebruiken en/of te up-cyclen.

#### 2.3 Randvoorwaarden

Naast ambities en doelstellingen zijn er ook een aantal randvoorwaarden die beide gemeenten stellen bij dit programma, waaraan moet worden voldaan:

- Participatie met inwoners, ondernemers en (kennis)instellingen (stakeholders)
- Inzetten op baankansen (SROI)
- Ruimtelijke kwaliteit / kwaliteitsniveau wegbeheer
- Circulair inkopen
- Veiligheid, comfort, beschikbaarheid en bereikbaarheid

[1] SMART is de afkorting van Specifiek, Meetbaar, Acceptabel, Realistisch en Tijdgebonden

4

Versie 2.0 – 29 november 2023

*Figure A.1: Policy objectives from the national government and the municipality of Enschede-Losser*

# APPENDIX B

| |
|---|
| **Fietspaden** |
| Frezen tussenlaag -aanbrengen tussenlaag AC 16 bind |
| Frezen tussenlaag -aanbrengen tussenlaag AC 16 bind Lynpave |
| Frezen bakken in tussenlaag - aanbrengen AC 16 bind |
| Frezen bakken in tussenlaag - aanbrengen AC 16 bind Lynpave |
| |
| Frezen deklaag - aanbrengen deklaag AC 11 surf zwart |
| Frezen deklaag - aanbrengen deklaag AC 11 rood |
| Frezen deklaag - aanbrengen AC 16 bind + aanbrengen rode slijtlaag |
| Frezen deklaag - aanbrengen AC 16 bind + aanbrengen rode laag possehl |
| Frezen deklaag - aanbrengen AC 11 surf zwart + kruisingsvlakken possehl |
| Frezen deklaag - aanbrengen AC 11 surf zwart grasfalt + kruisingsvlakken possehl |
| Frezen deklaag - aanbrengen deklaag SMA 08 rood |
| Frezen deklaag - aanbrengen deklaag SMA 08 rood wordend |
| Frezen deklaag - aanbrengen deklaag SMA 08 rood wordend Grasfalt |
| Frezen deklaag - aanbrengen deklaag rood ecofalt |
| |
| Gehele constructie + fundering vervangen? Reconstructie? |
| |
| **Hoofdwegen/wijkonstluitingswegen** |
| Frezen tussenlaag -aanbrengen tussenlaag AC 16 bind |
| Frezen tussenlaag -aanbrengen tussenlaag AC 16 bind Lynpave |
| Frezen tussenlaag -aanbrengen tussenlaag AC 16 bind gemodificeerd |
| Frezen bakken - aanbrengen AC 16 bind |
| Frezen bakken - aanbrengen AC 16 bind Lynpave |
| |
| Frezen deklaag - aanbrengen deklaag SMA |
| Frezen deklaag - aanbrengen deklaag SMA gemodificeerd |
| Frezen deklaag - aanbrengen deklaag SMA Lynpave |
| Frezen deklaag - aanbrengen deklaag SMA Grasfalt |
| Frezen deklaag - aanbrengen deklaag Surf Grasfalt |
| Frezen deklaag - aanbrengen deklaag surf Lynpave |
| Frezen deklaag - aanbrengen deklaag surf |
| Frezen deklaag - aanbrengen deklaag ecofalt |
| Aanbrengen EAB |
| Frezen bakken - vullen bakken met deklaag |
| |
| Gehele constructie + fundering vervangen? |
| toepassen wapeningsdoek? |
| |
| **Buitenwegen** |
| Aanbrengen Slijtlaag |
| Aanbrengen EAB |
| Frezen bakken teervrij + slijtlaag |
| Frezen bakken teerhoudend + slijtlaag |
| Overlagen met AC 16 bind + slijtlaag |
| Overlagen met AC 16 bind Lynpave + slijtlaag |
| Overlagen met AC 16 surf |
| Overlagen met AC 16 surf lynpave |
| Overlagen met AC 16 surf grasfalt |
| Overlagen met ecofalt |
| |
| Gehele constructie + fundering vervangen? Schuimbitumen etc? |
| toepassen wapeningsdoek? |
| |
| |
| opmerkingen: |
| wat te doen met teerhouden freesasfalt, bij voorkeur uit de keten halen |
| waar en hoe plaatsen we innovaties? |

*Figure B.1: Maintenance measures and asphalt mixtures per road type*

| | A | B | C | D | E | F | G | H | I | J | K |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 101 | Diversen | 1.00 | eur | [redacted] | | | | | | | |
| 102 | Eten | 7.00 | stuks | | | | | | | | |
| 103 | | | | | | | | | | | |
| 104 | | | | | | | | | | | |
| 105 | | | | | | | | | | | |
| 106 | **Fietspadset klein** | | | | | | | | | | |
| 107 | | | | | | | | | | | |
| 108 | **Omschrijving** | **Hoev** | **Eenh** | **Tarief** | **Bedrag** | **Toeslag** | **Nachttarief** | **Toeslag** | **Weekendtarief** | | **Toepas** |
| 109 | Asfaltafwerkmachine | 1.00 | dag | [redacted] | | | | | | | Bakken |
| 110 | Trilwals klein | 1.00 | dag | | | | | | | | Dagprod |
| 111 | Mobiele spuitketel | 1.00 | dag | | | | | | | | |
| 112 | Waterbak | 1.00 | dag | | | | | | | | |
| 113 | Uitvoerder | 8.00 | uur | | | | | | | | |
| 114 | Balkman | 10.00 | uur | | | | | | | | |
| 115 | Machinist | 20.00 | uur | | | | | | | | 1 bij afw |
| 116 | Afwerker | 20.00 | uur | | | | | | | | |
| 117 | Diversen | 1.00 | eur | | | | | | | | |
| 118 | Eten | 6.00 | stuks | | | | | | | | |
| 119 | | | | | | | | | | | |
| 120 | | | | | | | | | | | |
| 121 | | | | | | | | | | | |
| 122 | **Handploeg** | | | | | | | | | | |
| 123 | | | | | | | | | | | |
| 124 | **Omschrijving** | **Hoev** | **Eenh** | **Tarief** | **Bedrag** | **Toeslag** | **Nachttarief** | **Toeslag** | **Weekendtarief** | | **Toepas** |
| 125 | Trilwals klein | 1.00 | dag | [redacted] | | | | | | | Sleufjes |
| 126 | Kleefunit | 1.00 | dag | | | | | | | | Dagprod |
| 127 | Afwerker | 27.00 | uur | | | | | | | | |
| 128 | Diversen | 1.00 | eur | | | | | | | | |
| 129 | Eten | 3.00 | stuks | | | | | | | | |
| 130 | | | | | | | | | | | |
| 131 | | | | | | | | | | | |
| 132 | | | | | | | | | | | |
| 133 | | | | | | | | | | | |
| 134 | | | | | | | | | | | |
| 135 | | | | | | | | | | | |
| 136 | | | | | | | | | | | |

Blad1 | Blad2 tarieven asfaltsets | Blad3 tarieven slijtlagenploeg | Blad4 | +

*Figure B.2: Sample of Excel file 'Tarieven personeel 2023 (wijziging per 9 januari 2023)' from which asphaltsets, machinery, transport and personnel data is gathered*

# APPENDIX C

*Table C.1: All asphalt mixtures that are included in the tool*

| Top layer | Source |
|---|---|
| AC 11 surf 30% PR | (NTP, 2024) |
| AC 11 surf 30% PR Grasfalt | (NTP, 2024) |
| AC 11 surf 30% PR Lynpave | (NTP, 2024) |
| AC 11 surf 30% PR modified | (NTP, 2024) |
| AC 11 surf NO PR | (NTP, 2024) |
| AC 11 surf tilrood 70/100 3% | (NTP, 2024) |
| Cross planes Possehl | (NTP, 2024) |
| Red Ecofalt | (NTP, 2024) |
| Red layer Possehl | (NTP, 2024) |
| Red wear layer | (NTP, 2024) |
| SMA 8-11 | (NTP, 2024) |
| SMA 8-11 modified | (NTP, 2024) |
| SMA 8B 70/100 tilrood 3% | (NTP, 2024) |
| SMA NL 8B Grasfalt | (NTP, 2024) |
| SMA NL 8B Grasfalt roodwordend | (NTP, 2024) |
| **Intermediate layer** | **Source** |
| AC 16 bind 50% PR | (NTP, 2024) |
| AC 16 bind 50% PR modified | (NTP, 2024) |
| AC 16 bind 60% PR Lynpave | (NTP, 2024) |
| **Base layer** | **Source** |
| AC 16 base 50% PR | (NTP, 2024) |
| AC 16 base 50% PR modified | (NTP, 2024) |
| AC 16 base 60% PR Lynpave | (NTP, 2024) |
| AC 16 base 65% PR | (NTP, 2024) |
| AC 16 base 65% PR Lynpave | (NTP, 2024) |

*Table C.2: All asphaltsets that are included in the tool*

| Asphaltsets | Source |
|---|---|
| Asphaltset complete | (NTP, 2023) |
| Asphaltset complete - night | (NTP, 2023) |
| Asphaltset complete - weekend | (NTP, 2023) |
| Asphaltset RZR | (NTP, 2023) |
| Asphaltset RZR - night | (NTP, 2023) |
| Asphaltset RZR - weekend | (NTP, 2023) |
| Asphaltset seamless | (NTP, 2023) |
| Asphaltset seamless - night | (NTP, 2023) |
| Asphaltset seamless - weekend | (NTP, 2023) |
| Cycling path set large | (NTP, 2023) |
| Cycling path set large - night | (NTP, 2023) |
| Cycling path set large - weekend | (NTP, 2023) |
| Cycling path set small | (NTP, 2023) |
| Cycling path set small - night | (NTP, 2023) |
| Cycling path set small - weekend | (NTP, 2023) |
| Handteam | (NTP, 2023) |
| Handteam - night | (NTP, 2023) |

| | |
|---|---|
| Handteam - weekend | (NTP, 2023) |
| **Wear layer sets** | **Source** |
| Singular | (NTP, 2023) |
| Sprinkled | (NTP, 2023) |

*Table C.3: All machinery that is included in the tool*

| Machinery | Source |
|---|---|
| Asphalt paver | (NTP, 2023) |
| Emulsion bitumen truck | (NTP, 2023) |
| Low loader | (NTP, 2023) |
| Milling machine | (NTP, 2023) |
| Motorjapanner | (NTP, 2023) |
| Mobile crane | (NTP, 2023) |
| Mobile sprayer | (NTP, 2023) |
| Shovel | (NTP, 2023) |
| Site hut | (NTP, 2023) |
| Spreading tractor | (NTP, 2023) |
| Static roller | (NTP, 2023) |
| Surface cleaning truck | (NTP, 2023) |
| Sweeper truck | (NTP, 2023) |
| Tack unit | (NTP, 2023) |
| Tyred roller | (NTP, 2023) |
| Vibratory roller | (NTP, 2023) |
| Water tank | (NTP, 2023) |

# APPENDIX D

*Table D.1: MKI values per asphalt mixture and road layer*

| **Top layer (deklaag)** | | | *Production phase* | *Construction phase* | | *Use phase* | *Disposal phase* | *Beyond system phase* |
|---|---|---|---|---|---|---|---|---|
| **Name** | Unit | Lifespan (years) | A1-A3 | A4 | A5 | B1-B5 | C1-C4 | D |
| AC 11 surf 30% PR | ton | 14 | € 10.32 | € 0.38 | € 0.26 | € 0.08 | € 0.62 | -€ 3.08 |
| AC 11 surf 30% PR Grasfalt | ton | 14 | € 7.38 | € | € | € | € | -€ 3.06 |
| AC 11 surf 30% PR Lynpave | ton | 16 | € 8.44 | € | € | € | € | -€ 3.06 |
| AC 11 surf 30% PR modified | ton | 14 | € 11.65 | € 0.38 | € 0.26 | € 0.08 | € 0.62 | -€ 3.08 |
| AC 11 surf NO PR | ton | 14 | € 12.93 | € 0.38 | € 0.26 | € 0.08 | € 0.62 | -€ 4.37 |
| AC 11 surf tilrood 70/100 3% | ton | 14 | € 16.70 | € | € | € | € | -€ |
| Cross planes Possehl | ton | | € | € | € | € | € | -€ |
| Red Ecofalt | ton | 14 | € 7.60 | € | € | € | € | -€ |
| Red layer Possehl | ton | | € | € | € | € | € | -€ 4.37 |
| Red wear layer | ton | 8 | € 0.29 | € | € | € | € | -€ |
| SMA 8-11 | ton | 16 | € 13.81 | € 0.38 | € 0.26 | € 0.12 | € 0.62 | -€ 4.37 |
| SMA 8-11 modified | ton | 16 | € 15.78 | € 0.38 | € 0.26 | € 0.12 | € 0.62 | -€ 4.37 |
| SMA 8B 70/100 tilrood 3% | ton | 16 | € 18.80 | € | € | € | € | -€ 4.37 |
| SMA NL 8B Grasfalt | ton | 16 | € 10.04 | € 0.29 | € 0.26 | € 0.00 | € 0.62 | -€ 4.37 |
| SMA-NL 8B Grasfalt roodwordend | ton | 16 | € 7.83 | € 0.29 | € 0.26 | € 0.00 | € 0.62 | -€ 4.37 |
| **Intermediate layer (tussenlaag)** | | | | | | | | |
| AC 16 bind 50% PR | ton | 45 | € 5.91 | € 0.38 | € 0.14 | € 0 | € 0.8 | -€ 2.33 |
| AC 16 bind 50% PR modified | ton | 45 | € 6.49 | € 0.38 | € 0.14 | € 0 | € 0.8 | -€ 2.33 |
| AC 16 bind 60% PR Lynpave | ton | 45 | € 4.32 | € | € | € | € | -€ 1.86 |
| **Base layer (onderlaag)** | | | | | | | | |
| AC 16 base 50% PR | ton | 45 | € 5.91 | € 0.38 | € 0.14 | € 0 | € 0.8 | -€ 2.33 |
| AC 16 base 50% PR modified | ton | 45 | € 6.49 | € 0.38 | € 0.14 | € 0 | € 0.8 | -€ 2.33 |
| AC 16 base 60% PR Lynpave | ton | 45 | € 4.32 | € | € | € | € | -€ 1.86 |
| AC 16 base 65% PR | ton | 45 | € 3.81 | € | € | € | € | -€ 1.63 |
| AC 16 base 65% PR Lynpave | ton | 45 | € 3.83 | € | € | € | € | -€ 1.63 |

# APPENDIX E

*Table E.1: CO2 emission per asphalt mixture per road layer in kg $CO_2$/ton asphalt*

| **Top layer (deklaag)** | | *Production phase* | *Construction phase* | | *Use phase* | *Disposal phase* | *Beyond system phase* |
|---|---|---|---|---|---|---|---|
| **Name** | Unit | A1-A3 | A4 | A5 | B1-B5 | C1-C4 | D |
| AC 11 surf 30% PR | ton | 92.9 | 3.99 | 2.53 | 0 | 6.32 | -22.9 |
| AC 11 surf 30% PR Grasfalt | ton | 64.36 | | | | | -22.73 |
| AC 11 surf 30% PR Lynpave | ton | 72.82 | | | | | -22.73 |
| AC 11 surf 30% PR modified | ton | 105.3 | 3.99 | 2.53 | 0 | 6.32 | -22.9 |
| AC 11 surf NO PR | ton | 114.4 | 3.99 | 2.53 | 0 | 6.32 | -32.5 |
| AC 11 surf tilrood 70/100 3% | ton | 159.9 | | | | | -32.48 |
| Cross planes Possehl | ton | | | | | | |
| Red Ecofalt | ton | 58 | | | | | |
| Red layer Possehl | ton | | | | | | |
| Red wear layer | ton | 1.97 | | | | | |
| SMA 8-11 | ton | 117.1 | 3.99 | 2.53 | 0 | 6.32 | -32.5 |
| SMA 8-11 modified | ton | 135.5 | 3.99 | 2.53 | 0 | 6.32 | -32.5 |
| SMA 8B 70/100 tilrood 3% | ton | 175 | | | | | -32.48 |
| SMA NL 8B Grasfalt | ton | 86.7 | 2.63 | 2.55 | 0 | 6.33 | -32.48 |
| SMA-NL 8B Grasfalt roodwordend | ton | 94.41 | 2.63 | 2.55 | 0 | 6.33 | -32.48 |
| AC 16 bind 50% PR | ton | 57.4 | 3.99 | 1.4 | 0 | 8.24 | -17.3 |
| AC 16 bind 50% PR modified | ton | 62.8 | 3.99 | 1.4 | 0 | 8.24 | -17.3 |
| AC 16 bind 60% PR Lynpave | ton | 40.75 | | | | | -13.87 |
| AC 16 base 50% PR | ton | 57.4 | 3.99 | 1.4 | 0 | 8.24 | -17.3 |
| AC 16 base 50% PR modified | ton | 62.8 | 3.99 | 1.4 | 0 | 8.24 | -17.3 |
| AC 16 base 60% PR Lynpave | ton | 40.83 | | | | | -13.87 |
| AC 16 base 65% PR | ton | 38.68 | | | | | -12.14 |
| AC 16 base 65% PR Lynpave | ton | 38.85 | | | | | -12.14 |

*Table E.2: $CO_2$ emission per transport type*

| **Type: Transport within built-up area** | Unit | Emission per unit | |
|---|---|---|---|
| | | *Euro 5* | *Euro 6* |
| Passenger car diesel | ton $CO_2$/km | 0.00016 | 0.00016 |
| Passenger car gasoline | ton $CO_2$/km | 0.00019 | 0.00017 |
| Small bus diesel | ton $CO_2$/km | 0.00021 | 0.0002 |
| Small bus gasoline | ton $CO_2$/km | 0.00021 | 0.00019 |
| Trailer 400 kW | ton $CO_2$/km | 0.0013 | 0.0012 |
| Truck heavy 10x4 600 kW | ton $CO_2$/km | 0.0013 | 0.0012 |
| Truck medium 6x6 400 kW | ton $CO_2$/km | 0.00093 | 0.00078 |
| Truck medium 8x4 300 kW | ton $CO_2$/km | 0.00093 | 0.00078 |
| **Type: Transport outside built-up area** | Unit | Emission per unit | |
| | | *Euro 5* | *Euro 6* |
| Passenger car diesel | ton $CO_2$/km | 0.00014 | 0.00013 |
| Passenger car gasoline | ton $CO_2$/km | 0.00013 | 0.00011 |
| Small bus diesel | ton $CO_2$/km | 0.00018 | 0.00016 |
| Small bus gasoline | ton $CO_2$/km | 0.00013 | 0.00011 |
| Trailer 400 kW | ton $CO_2$/km | 0.00084 | 0.00085 |
| Truck heavy 10x4 600 kW | ton $CO_2$/km | 0.00086 | 0.00083 |
| Truck medium 6x6 400 kW | ton $CO_2$/km | 0.0006 | 0.00057 |
| Truck medium 8x4 300 kW | ton $CO_2$/km | 0.0006 | 0.00057 |
| **Type: Highway** | Unit | Emission per unit | |
| | | *Euro 5* | *Euro 6* |
| Passenger car diesel | ton $CO_2$/km | 0.00015 | 0.00012 |
| Passenger car gasoline | ton $CO_2$/km | 0.00017 | 0.00015 |
| Small bus diesel | ton $CO_2$/km | 0.0002 | 0.00016 |
| Small bus gasoline | ton $CO_2$/km | 0.00017 | 0.00015 |
| Trailer 400 kW | ton $CO_2$/km | 0.00068 | 0.00071 |
| Truck heavy 10x4 600 kW | ton $CO_2$/km | 0.00069 | 0.00066 |
| Truck medium 6x6 400 kW | ton $CO_2$/km | 0.0005 | 0.00094 |
| Truck medium 8x4 300 kW | ton $CO_2$/km | 0.0005 | 0.00094 |

*Table E.3: $CO_2$ emission per type asphalt set*

| **Type: Asphalt set** | Unit | Emission per unit |
|---|---|---|
| Asphaltset complete | ton $CO_2$/day | 1.369 |
| Asphaltset complete - night | ton $CO_2$/day | 1.369 |
| Asphaltset complete - weekend | ton $CO_2$/day | 1.369 |
| Asphaltset RZR | ton $CO_2$/day | 2.189 |
| Asphaltset RZR - night | ton $CO_2$/day | 2.189 |
| Asphaltset RZR - weekend | ton $CO_2$/day | 2.189 |
| Asphaltset seamless | ton $CO_2$/day | 1.998 |
| Asphaltset seamless - night | ton $CO_2$/day | 1.998 |
| Asphaltset seamless - weekend | ton $CO_2$/day | 1.998 |
| Cycling path set large | ton $CO_2$/day | 1.24 |
| Cycling path set large - night | ton $CO_2$/day | 1.24 |
| Cycling path set large - weekend | ton $CO_2$/day | 1.24 |
| Cycling path set small | ton $CO_2$/day | 0.63 |
| Cycling path set small - night | ton $CO_2$/day | 0.63 |
| Cycling path set small - weekend | ton $CO_2$/day | 0.63 |
| Handteam | ton $CO_2$/day | 0.249 |
| Handteam - night | ton $CO_2$/day | 0.249 |
| Handteam - weekend | ton $CO_2$/day | 0.249 |
| **Type: Wear layer set** | Unit | Emission per unit |
| Singular | ton $CO_2$/day | 0.532 |
| Sprinkled | ton $CO_2$/day | 0.652 |

*Table E.4: $CO_2$ emission of machinery per hour*

| Type: Machinery | Unit | Emission per unit | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 |
| Asphalt paver 100 kW | ton $CO_2$/hour | scna | 0.033 | 0.033 | 0.033 | 0.032 | 0.032 | 0.032 | 0.032 | 0.032 | 0.032 | 0.032 | 0.032 | 0.032 | 0.032 |
| Asphalt paver 60 kW | ton $CO_2$/hour | scna | 0.033 | 0.033 | 0.033 | 0.032 | 0.032 | 0.032 | 0.032 | 0.032 | 0.032 | 0.032 | 0.032 | 0.032 | 0.032 |
| Emulsion bitumen truck 250 kW | ton $CO_2$/hour | 0.052 | 0.052 | 0.052 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.056 | 0.056 | 0.056 | 0.056 | 0.056 | 0.056 |
| Low loader | ton $CO_2$/hour | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Milling machine W50 105 kW | ton $CO_2$/hour | scna | 0.1 | 0.1 | 0.1 | 0.098 | 0.098 | 0.098 | 0.098 | 0.098 | 0.095 | 0.095 | 0.095 | 0.095 | 0.095 |
| Milling machine W100 200 kW | ton $CO_2$/hour | 0.1 | 0.1 | 0.1 | 0.098 | 0.098 | 0.098 | 0.098 | 0.098 | 0.095 | 0.095 | 0.095 | 0.095 | 0.095 | 0.095 |
| Milling machine W130 240 kW | ton $CO_2$/hour | 0.1 | 0.1 | 0.1 | 0.098 | 0.098 | 0.098 | 0.098 | 0.098 | 0.095 | 0.095 | 0.095 | 0.095 | 0.095 | 0.095 |
| Mini dumper - Motorjapanner 20 kW | ton $CO_2$/hour | scna | scna | scna | scna | scna | scna | scna | scna | 0.0072 | 0.0072 | 0.0072 | 0.0072 | 0.0072 | 0.0072 |
| Mobile crane 150E 115 kW | ton $CO_2$/hour | scna | 0.02 | 0.02 | 0.02 | 0.019 | 0.019 | 0.019 | 0.019 | 0.019 | 0.0098 | 0.0098 | 0.0098 | 0.0098 | 0.0098 |
| Mobile crane 160E 105 kW | ton $CO_2$/hour | scna | 0.02 | 0.02 | 0.02 | 0.019 | 0.019 | 0.019 | 0.019 | 0.019 | 0.0095 | 0.0095 | 0.0095 | 0.0095 | 0.0095 |
| Mobile sprayer 50 kW | ton $CO_2$/hour | scna | scna | 0.052 | 0.052 | 0.052 | 0.052 | 0.052 | 0.052 | 0.013 | 0.013 | 0.013 | 0.013 | 0.013 | 0.013 |
| Shovel L70 125 kW | ton $CO_2$/hour | scna | 0.024 | 0.024 | 0.024 | 0.024 | 0.024 | 0.024 | 0.024 | 0.024 | 0.021 | 0.021 | 0.021 | 0.021 | 0.021 |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Shovel L90 140 kW | ton $CO_2$/hour | 0.026 | 0.026 | 0.026 | 0.026 | 0.026 | 0.026 | 0.026 | 0.026 | 0.023 | 0.023 | 0.023 | 0.023 | 0.023 | 0.023 |
| Site hut | ton $CO_2$/hour | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Spreading tractor 60 kW | ton $CO_2$/hour | scna | 0.014 | 0.014 | 0.014 | 0.014 | 0.014 | 0.014 | 0.014 | 0.014 | 0.012 | 0.012 | 0.012 | 0.012 | 0.012 |
| Static roller 25 kW | ton $CO_2$/hour | scna | scna | scna | scna | scna | scna | scna | scna | 0.0079 | 0.0079 | 0.0079 | 0.0079 | 0.0079 | 0.0079 |
| Surface cleaning truck 240 kW | ton $CO_2$/hour | 0.035 | 0.035 | 0.035 | 0.033 | 0.033 | 0.033 | 0.033 | 0.033 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 |
| Sweeper truck 120 kW | ton $CO_2$/hour | scna | 0.022 | 0.022 | 0.022 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 |
| Tack unit 20 kW | ton $CO_2$/hour | scna | scna | scna | scna | scna | scna | scna | scna | 0.0069 | 0.0069 | 0.0069 | 0.0069 | 0.0069 | 0.0069 |
| Tyred roller 60 kW | ton $CO_2$/hour | scna | 0.016 | 0.016 | 0.016 | 0.024 | 0.024 | 0.024 | 0.024 | 0.024 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 |
| Tyred roller 90 kW | ton $CO_2$/hour | scna | 0.023 | 0.023 | 0.023 | 0.024 | 0.024 | 0.024 | 0.024 | 0.024 | 0.022 | 0.022 | 0.022 | 0.022 | 0.022 |
| Vibratory roller 75 kW | ton $CO_2$/hour | scna | 0.019 | 0.019 | 0.019 | 0.024 | 0.024 | 0.024 | 0.024 | 0.024 | 0.018 | 0.018 | 0.018 | 0.018 | 0.018 |
| Vibratory roller 95 kW | ton $CO_2$/hour | scna | 0.024 | 0.024 | 0.024 | 0.024 | 0.024 | 0.024 | 0.024 | 0.024 | 0.023 | 0.023 | 0.023 | 0.023 | 0.023 |
| Water tank | ton $CO_2$/hour | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

# APPENDIX F

*Table F.1: Price per asphalt mixture for each road layer*

| **Top layer (deklaag)** | | |
|---|---|---|
| **Name** | **Unit** | **Price per unit** |
| AC 11 surf 30% PR | €/ton | 69.02 |
| AC 11 surf 30% PR Grasfalt | €/ton | 88.40 |
| AC 11 surf 30% PR Lynpave | €/ton | 70.97 |
| AC 11 surf 30% PR modified | €/ton | 76.35 |
| AC 11 surf NO PR | €/ton | 82.96 |
| AC 11 surf tilrood 70/100 3% | €/ton | 162.3 |
| Cross planes Possehl | €/$m^2$ | 180 |
| Red Ecofalt | €/ton | |
| Red layer Possehl | €/$m^2$ | 40 |
| Red wear layer | €/$m^2$ | 15 |
| SMA 8-11 | €/ton | 92.12 |
| SMA 8-11 modified | €/ton | 107.14 |
| SMA 8B 70/100 tilrood 3% | €/ton | 188.67 |
| SMA NL 8B Grasfalt | €/ton | 113.74 |
| SMA NL 8B Grasfalt roodwordend | €/ton | 167 |
| **Intermediate layer (tussenlaag)** | | |
| AC 16 bind 50% PR | €/ton | 50.35 |
| AC 16 bind 50% PR modified | €/ton | 48.43 |
| AC 16 bind 60% PR Lynpave | €/ton | 48.43 |
| **Base layer (onderlaag)** | | |
| AC 16 base 50% PR | €/ton | 50.35 |
| AC 16 base 50% PR modified | €/ton | 48.43 |
| AC 16 base 60% PR Lynpave | €/ton | 48.43 |
| AC 16 base 65% PR | €/ton | 41.84 |
| AC 16 base 65% PR Lynpave | €/ton | 43.53 |

*Table F.2: Price per unit for machinery category*

| Type: Machinery | Unit | Price per unit |
|---|---|---|
| Asphalt paver 60 kW | €/day | 690 |
| Asphalt paver 100 kW | €/day | 885 |
| Emulsion bitumen truck 250 kW | €/day | 575 |
| Low loader | €/hour | 20 |
| Milling machine W50 105 kW | €/hour | 210 |
| Milling machine W100 200 kW | €/hour | 420 |
| Milling machine W130 240 kW | €/hour | 475 |
| Mini dumper - Motorjapanner 20 kW | €/day | 140 |
| Mobile crane 150 105 kW | €/hour | 76.25 |
| Mobile crane 160 115 kW | €/hour | 79.25 |
| Mobile sprayer 50 kW | €/day | 120 |
| Shovel L70 125 kW | €/hour | 88 |
| Shovel L90 140 kW | €/hour | 96.50 |
| Site hut | €/day | 100 |
| Spreading tractor 60 kW | €/day | 60 |
| Static roller 25 kW | €/day | 170 |
| Surface cleaning truck 240 kW | €/hour | 209 |
| Sweeper truck 120 kW | €/hour | 139 |
| Tack unit 20 kW | €/day | 120 |
| Tyred roller 60 kW | €/day | 160 |
| Tyred roller 90 kW | €/day | 160 |
| Vibratory roller 75 kW | €/day | 190 |
| Vibratory roller 95 kW | €/day | 190 |
| Water tank | €/day | 150 |

*Table F.3: Price per unit for transport and personnel categories*

| Type: Transport | Unit | Price per unit |
|---|---|---|
| Passenger car diesel | €/hour | 15 |
| Passenger car gasoline | €/hour | 15 |
| Small bus diesel | €/hour | 25 |
| Small bus gasoline | €/hour | 25 |
| Trailer 400 kW | €/hour | 95 |
| Truck heavy 10x4 600 kW | €/hour | 99.25 |
| Truck medium 6x6 400 kW | €/hour | 91.5 |
| Truck medium 8x4 300 kW | €/hour | 92 |
| **Type: Personnel** | **Unit** | **Price per unit** |
| Asphalt coordinator | €/hour | 99.50 |
| Employee | €/hour | 55 |
| Executor | €/hour | 75.50 |
| Finisher | €/hour | 60 |
| Machinist | €/hour | 60 |

*Table F.4: Costs per type asphalt set*

| **Type: Asphalt set** | **Unit** | **Price per unit** |
|---|---|---|
| Asphaltset complete | €/day | 7675 |
| Asphaltset complete - night | €/day | 9920 |
| Asphaltset complete - weekend | €/day | 11630 |
| Asphaltset RZR | €/day | 13800 |
| Asphaltset RZR - night | €/day | 18260 |
| Asphaltset RZR - weekend | €/day | 22060 |
| Asphaltset seamless | €/day | 12160 |
| Asphaltset seamless - night | €/day | 15990 |
| Asphaltset seamless - weekend | €/day | 21420 |
| Cycling path set large | €/day | 5960 |
| Cycling path set large - night | €/day | 7900 |
| Cycling path set large - weekend | €/day | 9730 |
| Cycling path set small | €/day | 4775 |
| Cycling path set small - night | €/day | 6375 |
| Cycling path set small - weekend | €/day | 7600 |
| Handteam | €/day | 2075 |
| Handteam - night | €/day | 2940 |
| Handteam - weekend | €/day | 3600 |
| **Type: Wear layer set** | **Unit** | **Price per unit** |
| Singular | €/day | 5386 |
| Sprinkled | €/day | 6359 |

# APPENDIX G.1

| ASPHALT | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Asphalt top layer (deklaag)** | | | *Production phase* | *Construction phase* | | *Use phase* | *Disposal phase* | *Beyond system phase* |
| **Name** | Unit | Lifespan | A1-A3 | A4 | A5 | B1-B5 | C1-C4 | D |
| **Select** | unit | | 0 | 0 | 0 | 0 | 0 | 0 |
| AC 11 surf 30% PR | ton | 14 | € 10.32 | € 0.38 | € 0.26 | € 0.08 | € 0.62 | -€ 3.08 |
| AC 11 surf 30% PR Grasfalt | ton | 14 | € 7.38 | | | | | -€ 3.06 |
| AC 11 surf 30% PR Lynpave | ton | 16 | € 8.44 | | | | | -€ 3.06 |
| AC 11 surf 30% PR modified | ton | 14 | € 11.65 | € 0.38 | € 0.26 | € 0.08 | € 0.62 | -€ 3.08 |
| AC 11 surf NO PR | ton | 14 | € 12.93 | € 0.38 | € 0.26 | € 0.08 | € 0.62 | -€ 4.37 |
| AC 11 surf tilrood 70/100 3% | ton | 14 | € 16.70 | | | | | -€ 4.37 |
| Cross planes Possehl | m2 | | | | | | | |
| Red Ecofalt | ton | 14 | € 7.60 | | | | | € 0.00 |
| Red layer Possehl | m2 | | | | | | | |
| Red wear layer | m2 | 8 | € 0.29 | | | | | |
| SMA 8-11 | ton | 16 | € 13.81 | € 0.38 | € 0.26 | € 0.12 | € 0.62 | -€ 4.37 |
| SMA 8-11 modified | ton | 16 | € 15.78 | € 0.38 | € 0.26 | € 0.12 | € 0.62 | -€ 4.37 |
| SMA 8B 70/100 tilrood 3% | ton | 16 | € 18.80 | | | | | -€ 4.37 |
| SMA NL 8B Grasfalt | ton | 16 | € 10.04 | € 0.29 | € 0.26 | € 0.00 | € 0.62 | -€ 4.37 |
| SMA NL 8B Grasfalt roodwordend | ton | 16 | € 7.83 | € 0.29 | € 0.26 | € 0.00 | € 0.62 | -€ 4.37 |
| **Asphalt intermediate layer (tussenlaag)** | | | *Production phase* | *Construction phase* | | *Use phase* | *Disposal phase* | *Beyond system phase* |
| **Name** | Unit | Lifespan | A1-A3 | A4 | A5 | B1-B5 | C1-C4 | D |
| **Select** | unit | | 0 | 0 | 0 | 0 | 0 | 0 |
| AC 16 bind 50% PR | ton | 45 | 5.91 | 0.38 | 0.14 | 0 | 0.8 | -€ 2.33 |
| AC 16 bind 50% PR modified | ton | 45 | 6.49 | 0.38 | 0.14 | 0 | 0.8 | -€ 2.33 |
| AC 16 bind 60% PR Lynpave | ton | 45 | 4.32 | | | | | -€ 1.86 |
| **Asphalt base layer (onderlaag)** | | | *Production phase* | *Construction phase* | | *Use phase* | *Disposal phase* | *Beyond system phase* |
| **Name** | Unit | Lifespan | A1-A3 | A4 | A5 | B1-B5 | C1-C4 | D |
| **Select** | unit | | 0 | 0 | 0 | 0 | 0 | 0 |
| AC 16 base 50% PR | ton | 45 | 5.91 | 0.38 | 0.14 | 0 | 0.8 | -€ 2.33 |
| AC 16 base 50% PR modified | ton | 45 | 6.49 | 0.38 | 0.14 | 0 | 0.8 | -€ 2.33 |
| AC 16 base 60% PR Lynpave | ton | 45 | 4.32 | | | | | -€ 1.86 |
| AC 16 base 65% PR | ton | 45 | 3.81 | | | | | -€ 1.63 |
| AC 16 base 65% PR Lynpave | ton | 45 | 3.83 | | | | | -€ 1.63 |

*Figure G.1a: Datasheet of MKI values per asphalt mixture per layer*

| Asphalt top layer (deklaag) | | |
|---|---|---|
| **Name** | **Unit** | **Lifespan** |
| **Select** | unit | |
| AC 11 surf 30% PR | ton | 14 |
| AC 11 surf 30% PR Grasfalt | ton | 14 |
| AC 11 surf 30% PR Lynpave | ton | 16 |
| AC 11 surf 30% PR modified | ton | 14 |
| AC 11 surf NO PR | ton | 14 |
| AC 11 surf tilrood 70/100 3% | ton | 14 |
| Cross planes Possehl | m2 | |
| Red Ecofalt | ton | 14 |
| Red layer Possehl | m2 | |
| Red wear layer | m2 | 8 |
| SMA 8-11 | ton | 16 |
| SMA 8-11 modified | ton | 16 |
| SMA 8B 70/100 tilrood 3% | ton | 16 |
| SMA NL 8B Grasfalt | ton | 16 |
| SMA NL 8B Grasfalt roodwordend | ton | 16 |
| **Asphalt intermediate layer (tussenlaag)** | | |
| **Name** | **Unit** | **Lifespan** |
| **Select** | unit | |
| AC 16 bind 50% PR | ton | 45 |
| AC 16 bind 50% PR modified | ton | 45 |
| AC 16 bind 60% PR Lynpave | ton | 45 |
| **Asphalt base layer (onderlaag)** | | |
| **Name** | **Unit** | **Lifespan** |
| **Select** | unit | |
| AC 16 base 50% PR | ton | 45 |
| AC 16 base 50% PR modified | ton | 45 |
| AC 16 base 60% PR Lynpave | ton | 45 |
| AC 16 base 65% PR | ton | 45 |
| AC 16 base 65% PR Lynpave | ton | 45 |

*Figure G.1b: Datasheet of lifespan values per asphalt mixture per layer*

# APPENDIX G.2

| ASPHALT | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Asphalt top layer (deklaag)** | | | Production phase | Construction phase | | Use phase | Disposal phase | Beyond system phase | Phase A1-A3 + D |
| **Name** | Unit | Lifespan | A1-A3 | A4 | A5 | B1-B5 | C1-C4 | D | |
| **Select** | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AC 11 surf 30% PR | ton | 14 | 92.9 | 3.99 | 2.53 | 0 | 6.32 | -22.9 | 0.07 |
| AC 11 surf 30% PR Grasfalt | ton | 14 | 64.36 | | | | | -22.73 | 0.04163 |
| AC 11 surf 30% PR Lynpave | ton | 14 | 72.82 | | | | | -22.73 | 0.05009 |
| AC 11 surf 30% PR modified | ton | 14 | 105.3 | 3.99 | 2.53 | 0 | 6.32 | -22.9 | 0.0824 |
| AC 11 surf NO PR | ton | 14 | 114.4 | 3.99 | 2.53 | 0 | 6.32 | -32.5 | 0.0819 |
| AC 11 surf tilrood 70/100 3% | ton | 14 | 159.9 | | | | | -32.48 | 0.12742 |
| Cross planes Possehl | ton | | | | | | | | 0 |
| Red Ecofalt | ton | 14 | 58 | | | | | | 0.058 |
| Red layer Possehl | m2 | | | | | | | | 0 |
| Red wear layer | m2 | 8 | 1.97 | | | | | | 0.00197 |
| SMA 8-11 | ton | 16 | 117.1 | 3.99 | 2.53 | 0 | 6.32 | -32.5 | 0.0846 |
| SMA 8-11 modified | ton | 16 | 135.5 | 3.99 | 2.53 | 0 | 6.32 | -32.5 | 0.103 |
| SMA 8B 70/100 tilrood 3% | ton | 16 | 175 | | | | | -32.48 | 0.14252 |
| SMA NL 8B Grasfalt | ton | 16 | 86.7 | 2.63 | 2.55 | 0 | 6.33 | -32.48 | 0.05422 |
| SMA NL 8B Grasfalt roodwordend | ton | 16 | 94.41 | 2.63 | 2.55 | 0 | 6.33 | -32.48 | 0.06193 |
| **Asphalt intermediate layer (tussenlaag)** | | | Production phase | Construction phase | | Use phase | Disposal phase | Beyond system phase | |
| **Name** | Unit | Lifespan | A1-A3 | A4 | A5 | B1-B5 | C1-C4 | D | |
| **Select** | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AC 16 bind 50% PR | ton | 45 | 57.4 | 3.99 | 1.4 | 0 | 8.24 | -17.3 | 0.0401 |
| AC 16 bind 50% PR modified | ton | 45 | 62.8 | 3.99 | 1.4 | 0 | 8.24 | -17.3 | 0.0455 |
| AC 16 bind 60% PR Lynpave | ton | 45 | 40.75 | | | | | -13.87 | 0.02688 |
| **Asphalt base layer (onderlaag)** | | | Production phase | Construction phase | | Use phase | Disposal phase | Beyond system phase | |
| **Name** | Unit | Lifespan | A1-A3 | A4 | A5 | B1-B5 | C1-C4 | D | |
| **Select** | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AC 16 base 50% PR | ton | 45 | 57.4 | 3.99 | 1.4 | 0 | 8.24 | -17.3 | 0.0401 |
| AC 16 base 50% PR modified | ton | 45 | 62.8 | 3.99 | 1.4 | 0 | 8.24 | -17.3 | 0.0455 |
| AC 16 base 60% PR Lynpave | ton | 45 | 40.83 | | | | | -13.87 | 0.02696 |
| AC 16 base 65% PR | ton | 45 | 38.68 | | | | | -12.14 | 0.02654 |
| AC 16 base 65% PR Lynpave | ton | 45 | 38.85 | | | | | -12.14 | 0.02671 |

*Figure G.2a: Datasheet of $CO_2$ values per asphalt mixture per layer*

| Type: Asphaltsets | ton/day | | | | | | |
|---|---|---|---|---|---|---|---|
| Select | 0 | | | | | | |
| Asphaltset complete | 1.369 | 0.32 | 0.079 | 0.18 | 0.23 | 0.56 | |
| Asphaltset complete - night | 1.369 | 0.32 | 0.079 | 0.18 | 0.23 | 0.56 | |
| Asphaltset complete - weekend | 1.369 | 0.32 | 0.079 | 0.18 | 0.23 | 0.56 | |
| Asphaltset RZR | 2.189 | 0.32 | 0.64 | 0.079 | 0.36 | 0.23 | 0.56 |
| Asphaltset RZR - night | 2.189 | 0.32 | 0.64 | 0.079 | 0.36 | 0.23 | 0.56 |
| Asphaltset RZR - weekend | 2.189 | 0.32 | 0.64 | 0.079 | 0.36 | 0.23 | 0.56 |
| Asphaltset seamless | 1.998 | 0.64 | 0.158 | 0.18 | 0.46 | 0.56 | |
| Asphaltset seamless - night | 1.998 | 0.64 | 0.158 | 0.18 | 0.46 | 0.56 | |
| Asphaltset seamless - weekend | 1.998 | 0.64 | 0.158 | 0.18 | 0.46 | 0.56 | |
| Cycling path set large | 1.24 | 0.32 | 0.36 | 0.56 | | | |
| Cycling path set large - night | 1.24 | 0.32 | 0.36 | 0.56 | | | |
| Cycling path set large - weekend | 1.24 | 0.32 | 0.36 | 0.56 | | | |
| Cycling path set small | 0.63 | 0.32 | 0.18 | 0.13 | | | |
| Cycling path set small - night | 0.63 | 0.32 | 0.18 | 0.13 | | | |
| Cycling path set small - weekend | 0.63 | 0.32 | 0.18 | 0.13 | | | |
| Handteam | 0.249 | 0.18 | 0.069 | | | | |
| Handteam - night | 0.249 | 0.18 | 0.069 | | | | |
| Handteam - weekend | 0.249 | 0.18 | 0.069 | | | | |

| Type: Wear layer sets | ton/day (excluding trucks) | | | |
|---|---|---|---|---|
| Select | 0 | | | |
| Singular | 0.532 | 0.24 | 0.22 | 0.072 |
| Sprinkled | 0.652 | 0.36 | 0.22 | 0.072 |

ton/hour — scna: stage class not acceptable

| Type: Machinery | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Select | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Asphalt paver 100 kW | scna | scna | scna | scna | scna | scna | scna | scna | scna | scna | scna |
| Asphalt paver 60 kW | scna | scna | scna | scna | scna | scna | scna | scna | scna | scna | scna |
| Emulsion bitumen truck 250 kW | scna | scna | scna | scna | scna | scna | scna | scna | scna | scna | 0.052 |
| Low loader | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Milling machine W50 105 kW | scna | scna | scna | scna | scna | scna | scna | scna | scna | scna | scna |
| Milling machine W100 200 kW | scna | scna | scna | scna | scna | scna | scna | scna | scna | scna | 0.1 |
| Milling machine W130 240 kW | scna | scna | scna | scna | scna | scna | scna | scna | scna | scna | 0.1 |
| Mini dumper - Motorjapanner 20 kW | scna | scna | scna | scna | scna | scna | scna | scna | scna | scna | scna |
| Mobile crane 150E 115 kW | scna | scna | scna | scna | scna | scna | scna | scna | scna | scna | scna |
| Mobile crane 160E 105 kW | scna | scna | scna | scna | scna | scna | scna | scna | scna | scna | scna |
| Mobile sprayer 50 kW | scna | scna | scna | scna | scna | scna | scna | scna | scna | scna | scna |
| Shovel L70 125 kW | scna | scna | scna | scna | scna | scna | scna | scna | scna | scna | scna |
| Shovel L90 140 kW | scna | scna | scna | scna | scna | scna | scna | scna | scna | scna | 0.026 |
| Site hut | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Spreading tractor 60 kW | scna | scna | scna | scna | scna | scna | scna | scna | scna | scna | scna |
| Static roller 25 kW | scna | scna | scna | scna | scna | scna | scna | scna | scna | scna | scna |
| Surface cleaning truck 240 kW | scna | scna | scna | scna | scna | scna | scna | scna | scna | scna | 0.035 |
| Sweeper truck 120 kW | scna | scna | scna | scna | scna | scna | scna | scna | scna | scna | scna |
| Tack unit 20 kW | scna | scna | scna | scna | scna | scna | scna | scna | scna | scna | scna |
| Tyred roller 60 kW | scna | scna | scna | scna | scna | scna | scna | scna | scna | scna | scna |
| Tyred roller 90 kW | scna | scna | scna | scna | scna | scna | scna | scna | scna | scna | scna |
| Vibratory roller 75 kW | scna | scna | scna | scna | scna | scna | scna | scna | scna | scna | scna |
| Vibratory roller 95 kW | scna | scna | scna | scna | scna | scna | scna | scna | scna | scna | scna |

| Type: Machinery | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Select | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Asphalt paver 100 kW | 0.033 | 0.033 | 0.033 | 0.032 | 0.032 | 0.032 | 0.032 | 0.032 | 0.032 | 0.032 | 0.032 | 0.032 | 0.032 |
| Asphalt paver 60 kW | 0.033 | 0.033 | 0.033 | 0.032 | 0.032 | 0.032 | 0.032 | 0.032 | 0.032 | 0.032 | 0.032 | 0.032 | 0.032 |
| Emulsion bitumen truck 250 kW | 0.052 | 0.052 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.056 | 0.056 | 0.056 | 0.056 | 0.056 | 0.056 |
| Low loader | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Milling machine W50 105 kW | 0.1 | 0.1 | 0.1 | 0.098 | 0.098 | 0.098 | 0.098 | 0.098 | 0.095 | 0.095 | 0.095 | 0.095 | 0.095 |
| Milling machine W100 200 kW | 0.1 | 0.1 | 0.098 | 0.098 | 0.098 | 0.098 | 0.098 | 0.095 | 0.095 | 0.095 | 0.095 | 0.095 | 0.095 |
| Milling machine W130 240 kW | 0.1 | 0.1 | 0.098 | 0.098 | 0.098 | 0.098 | 0.098 | 0.095 | 0.095 | 0.095 | 0.095 | 0.095 | 0.095 |
| Mini dumper - Motorjapanner 20 kW | scna | scna | scna | scna | scna | scna | scna | 0.0072 | 0.0072 | 0.0072 | 0.0072 | 0.0072 | 0.0072 |
| Mobile crane 150E 115 kW | 0.02 | 0.02 | 0.02 | 0.019 | 0.019 | 0.019 | 0.019 | 0.019 | 0.0098 | 0.0098 | 0.0098 | 0.0098 | 0.0098 |
| Mobile crane 160E 105 kW | 0.02 | 0.02 | 0.02 | 0.019 | 0.019 | 0.019 | 0.019 | 0.019 | 0.0095 | 0.0095 | 0.0095 | 0.0095 | 0.0095 |
| Mobile sprayer 50 kW | scna | 0.052 | 0.052 | 0.052 | 0.052 | 0.052 | 0.052 | 0.013 | 0.013 | 0.013 | 0.013 | 0.013 | 0.013 |
| Shovel L70 125 kW | 0.024 | 0.024 | 0.024 | 0.024 | 0.024 | 0.024 | 0.024 | 0.024 | 0.021 | 0.021 | 0.021 | 0.021 | 0.021 |
| Shovel L90 140 kW | 0.026 | 0.026 | 0.026 | 0.026 | 0.026 | 0.026 | 0.026 | 0.023 | 0.023 | 0.023 | 0.023 | 0.023 | 0.023 |
| Site hut | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Spreading tractor 60 kW | 0.014 | 0.014 | 0.014 | 0.014 | 0.014 | 0.014 | 0.014 | 0.014 | 0.012 | 0.012 | 0.012 | 0.012 | 0.012 |
| Static roller 25 kW | scna | scna | scna | scna | scna | scna | scna | 0.0079 | 0.0079 | 0.0079 | 0.0079 | 0.0079 | 0.0079 |
| Surface cleaning truck 240 kW | 0.035 | 0.035 | 0.033 | 0.033 | 0.033 | 0.033 | 0.033 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 |
| Sweeper truck 120 kW | 0.022 | 0.022 | 0.022 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 |
| Tack unit 20 kW | scna | scna | scna | scna | scna | scna | scna | 0.0069 | 0.0069 | 0.0069 | 0.0069 | 0.0069 | 0.0069 |
| Tyred roller 60 kW | 0.016 | 0.016 | 0.016 | 0.024 | 0.024 | 0.024 | 0.024 | 0.024 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 |
| Tyred roller 90 kW | 0.023 | 0.023 | 0.023 | 0.024 | 0.024 | 0.024 | 0.024 | 0.024 | 0.022 | 0.022 | 0.022 | 0.022 | 0.022 |
| Vibratory roller 75 kW | 0.019 | 0.019 | 0.019 | 0.024 | 0.024 | 0.024 | 0.024 | 0.024 | 0.018 | 0.018 | 0.018 | 0.018 | 0.018 |
| Vibratory roller 95 kW | 0.024 | 0.024 | 0.024 | 0.024 | 0.024 | 0.024 | 0.024 | 0.024 | 0.023 | 0.023 | 0.023 | 0.023 | 0.023 |

*Figure G.2b: Datasheet of $CO_2$ emissions per asphaltset or machinery depending on year of construction*

| Within built-up area | Per km | Per km |
|---|---|---|
| Type: Transport | Euro 5 | Euro 6 |
| Select | 0 | 0 |
| Passenger car diesel | 0.00016 | 0.00016 |
| Passenger car gasoline | 0.00019 | 0.00017 |
| Small bus diesel | 0.00021 | 0.0002 |
| Small bus gasoline | 0.00021 | 0.00019 |
| Trailer 400 kW | 0.0013 | 0.0012 |
| Truck heavy 10x4 600 kW | 0.0013 | 0.0012 |
| Truck medium 6x6 400 kW | 0.00093 | 0.00078 |
| Truck medium 8x4 300 kW | 0.00093 | 0.00078 |
| | | |
| | Table for sum | |
| | Euro 5 | 2 |
| | Euro 6 | 3 |
| | | |
| Outside built-up area | | |
| Type: Transport | Euro 5 | Euro 6 |
| Select | 0 | 0 |
| Passenger car diesel | 0.00014 | 0.00013 |
| Passenger car gasoline | 0.00013 | 0.00011 |
| Small bus diesel | 0.00018 | 0.00016 |
| Small bus gasoline | 0.00013 | 0.00011 |
| Trailer 400 kW | 0.00084 | 0.00085 |
| Truck heavy 10x4 600 kW | 0.00086 | 0.00083 |
| Truck medium 6x6 400 kW | 0.0006 | 0.00057 |
| Truck medium 8x4 300 kW | 0.0006 | 0.00057 |
| | | |
| | Table for sum | |
| | Euro 5 | 2 |
| | Euro 6 | 3 |
| | | |
| Highway | | |
| Type: Transport | Euro 5 | Euro 6 |
| Select | 0 | 0 |
| Passenger car diesel | 0.00015 | 0.00012 |
| Passenger car gasoline | 0.00017 | 0.00015 |
| Small bus diesel | 0.0002 | 0.00016 |
| Small bus gasoline | 0.00017 | 0.00015 |
| Trailer 400 kW | 0.00068 | 0.00071 |
| Truck heavy 10x4 600 kW | 0.00069 | 0.00066 |
| Truck medium 6x6 400 kW | 0.0005 | 0.00094 |
| Truck medium 8x4 300 kW | 0.0005 | 0.00094 |

*Figure G.2c: $CO_2$ emissions per transport type per road category depending on fuel type*

# APPENDIX G.3

| Asphalt top layer (deklaag) | Unit | Price per unit (€) |
|---|---|---|
| **Select** | unit | 0 |
| AC 11 surf 30% PR | ton | 69.02 |
| AC 11 surf 30% PR Grasfalt | ton | 88.4 |
| AC 11 surf 30% PR Lynpave | ton | 70.97 |
| AC 11 surf 30% PR modified | ton | 76.35 |
| AC 11 surf NO PR | ton | 82.96 |
| AC 11 surf tilrood 70/100 3% | ton | 162.3 |
| Cross planes Possehl | m2 | 180 |
| Red Ecofalt | ton | |
| Red layer Possehl | m2 | 40 |
| Red wear layer | m2 | 15 |
| SMA 8-11 | ton | 92.12 |
| SMA 8-11 modified | ton | 107.14 |
| SMA 8B 70/100 tilrood 3% | ton | 188.67 |
| SMA NL 8B Grasfalt | ton | 113.74 |
| SMA NL 8B Grasfalt roodwordend | ton | 167 |
| **Asphalt intermediate layer (tussenlaag)** | | |
| **Select** | unit | 0 |
| AC 16 bind 50% PR | ton | 50.35 |
| AC 16 bind 50% PR modified | ton | 48.43 |
| AC 16 bind 60% PR Lynpave | ton | 48.43 |
| **Asphalt base layer (onderlaag)** | | |
| **Select** | unit | 0 |
| AC 16 base 50% PR | ton | 50.35 |
| AC 16 base 50% PR modified | ton | 48.43 |
| AC 16 base 60% PR Lynpave | ton | 48.43 |
| AC 16 base 65% PR | ton | 41.84 |
| AC 16 base 65% PR Lynpave | ton | 43.53 |

*Figure G.3a: Datasheet of costs per ton or m2 asphalt per layer*

| | *Travel costs and surcharges included* | |
|---|---|---|
| Type: Asphaltsets | *€/ day* | |
| Select | 0 | *Night: 150%* |
| Asphaltset complete | 7675 | *Weekend: 200%* |
| Asphaltset complete - night | 9920 | |
| Asphaltset complete - weekend | 11630 | |
| Asphaltset RZR | 13800 | |
| Asphaltset RZR - night | 18260 | |
| Asphaltset RZR - weekend | 22060 | |
| Asphaltset seamless | 12160 | |
| Asphaltset seamless - night | 15990 | |
| Asphaltset seamless - weekend | 21420 | |
| Cycling path set large | 5960 | |
| Cycling path set large - night | 7900 | |
| Cycling path set large - weekend | 9730 | |
| Cycling path set small | 4775 | |
| Cycling path set small - night | 6375 | |
| Cycling path set small - weekend | 7600 | |
| Handteam | 2075 | |
| Handteam - night | 2940 | |
| Handteam - weekend | 3600 | |
| | | |
| Type: Wear layer set | *€/ day* | |
| Select | 0 | |
| Singular | 5386 | |
| Sprinkled | 6359 | |

*Figure G.3c: Datasheet of costs per day per asphalt or wear layer set*

| Type: Machinery | *€/unit* | |
|---|---|---|
| Select | 0 | unit |
| Asphalt paver 100 kW | 885 | day |
| Asphalt paver 60 kW | 690 | day |
| Emulsion bitumen truck 250 kW | 575 | day |
| Low loader | 20 | hour |
| Milling machine W50 105 kW | 210 | hour |
| Milling machine W100 200 kW | 420 | hour |
| Milling machine W130 240 kW | 475 | hour |
| Mini dumper - Motorjapanner 20 kW | 140 | day |
| Mobile crane 150E 105 kW | 76.25 | hour |
| Mobile crane 160E 115 kW | 79.25 | hour |
| Mobile sprayer 50 kW | 120 | day |
| Shovel L70 125 kW | 88 | hour |
| Shovel L90 140 kW | 96.5 | hour |
| Site hut | 100 | day |
| Spreading tractor 60 kW | 60 | day |
| Static roller 25 kW | 170 | day |
| Surface cleaning truck 240 kW | 209 | hour |
| Sweeper truck 120 kW | 139 | hour |
| Tack unit 20 kW | 120 | day |
| Tyred roller 60 kW | 160 | day |
| Tyred roller 90 kW | 160 | day |
| Vibratory roller 75 kW | 190 | day |
| Vibratory roller 95 kW | 190 | day |
| Water tank | 150 | day |
| | | |
| Type: Transport | *€/hour including fuel* | |
| Select | 0 | |
| Passenger car diesel | 15 | |
| Passenger car gasoline | 15 | |
| Small bus diesel | 25 | |
| Small bus gasoline | 25 | |
| Trailer 400 kW | 95 | |
| Truck heavy 10x4 600 kW | 99.25 | |
| Truck medium 6x6 400 kW | 91.5 | |
| Truck medium 8x4 300 kW | 92 | |
| | | |
| Type: Personnel | *€/hour* | |
| Select | 0 | |
| Asphaltcoordinator | 99.5 | |
| Employee | 55 | |
| Executor | 75.5 | |
| Finisher | 60 | |
| Machinist | 60 | |

*Figure G.3b: Costs per day and hour per type equipment or personnel*

# APPENDIX H

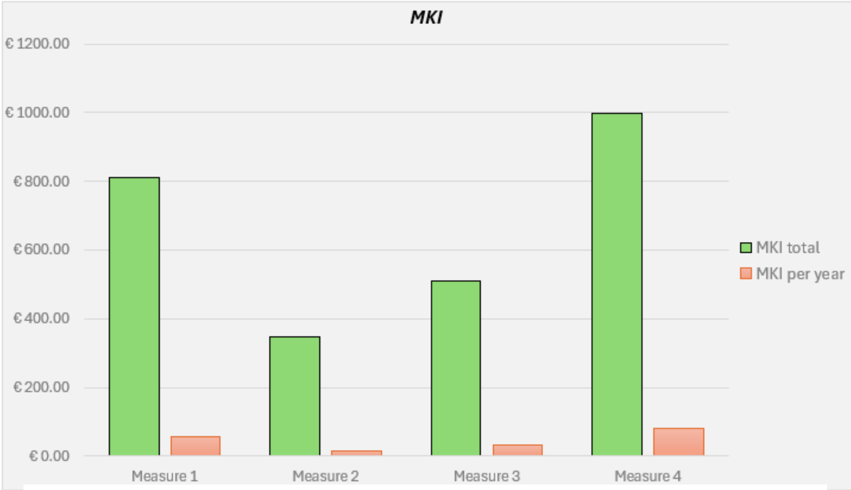


*Figure H.1: MKI in total and per year per measure*

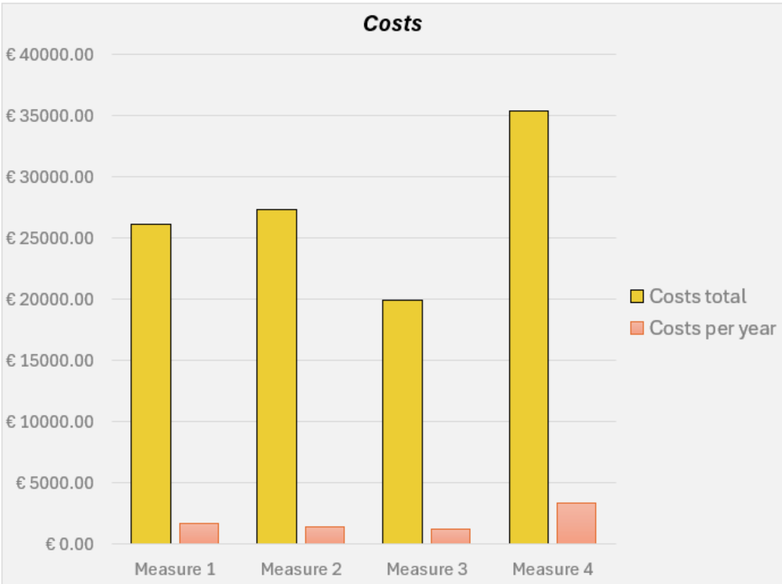


*Figure H.2: Costs in total and per year per measure*

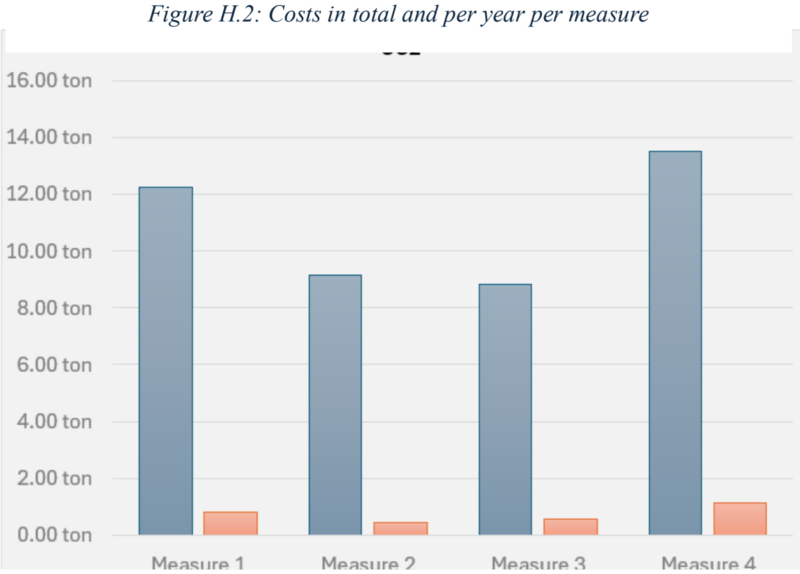


*Figure H.3: CO2 emission in total and per year per measure*

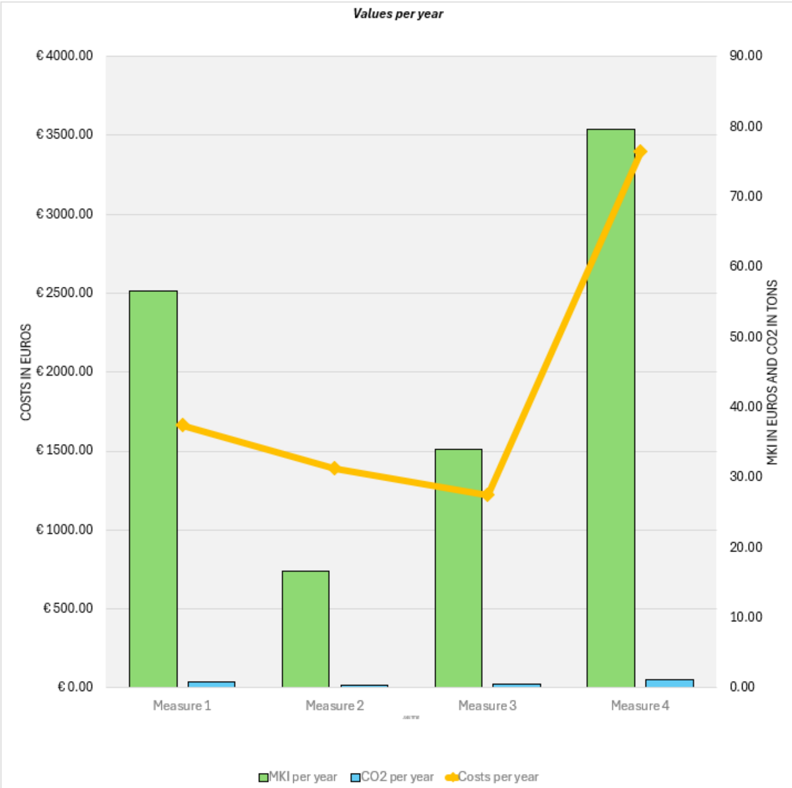


*Figure H.5: MKI, CO2 and costs per year per measure displayed in one graph*

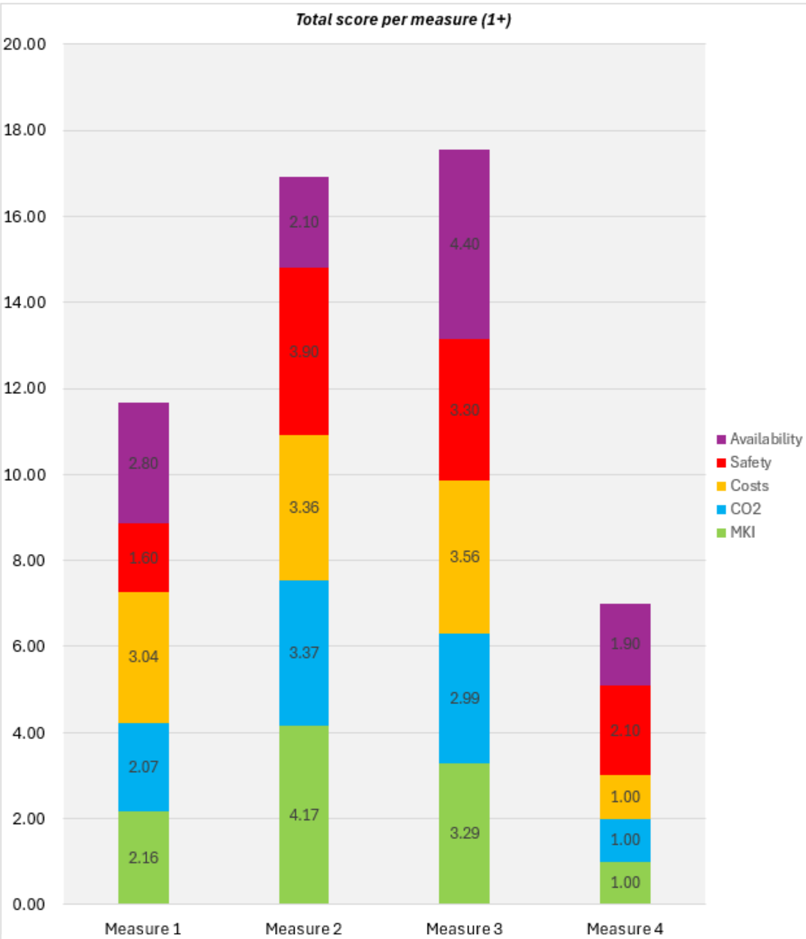


*Figure H.4: Total generalised score per measure*


*Figure H.6: Score of each measure plotted against the costs per year*

# APPENDIX I

*Table I.1: Sources of MKI regarding asphalt mixtures and lifespans*

| ***Asphalt mixtures*** | ***MKI*** | ***Lifespan*** |
|---|---|---|
| **Top layer** | **Source** | **Source** |
| AC 11 surf 30% PR | (Ecochain & TNO, 2022) | (Ecochain & TNO, 2022) |
| AC 11 surf 30% PR Grasfalt | (Ecochain & ACB, 2021) | (Ecochain & ACB, 2021) |
| AC 11 surf 30% PR Lynpave | (Ecochain & ACB, 2021) | (Ecochain & ACB, 2021) |
| AC 11 surf 30% PR modified | (Ecochain & TNO, 2022) | (Ecochain & TNO, 2022) |
| AC 11 surf NO PR | (Ecochain & TNO, 2022) | (Ecochain & TNO, 2022) |
| AC 11 surf tilrood 70/100 3% | (Ecochain & ACB, 2021) | (Ecochain & ACB, 2021) |
| Cross planes Possehl | | |
| Red Ecofalt | (Ecofalt, 2023) | (Ecofalt, 2023) |
| Red layer Possehl | | |
| Red wear layer | (Roelofs, 2024) | (Roelofs, 2024) |
| SMA 8-11 | (Ecochain & TNO, 2022) | (Ecochain & TNO, 2022) |
| SMA 8-11 modified | (Ecochain & TNO, 2022) | (Ecochain & TNO, 2022) |
| SMA 8B 70/100 tilrood 3% | (Ecochain & ACB, 2021) | (NTP, 2024) |
| SMA NL 8B Grasfalt | (Ecochain & ACB, 2021) | (NTP, 2024) |
| SMA NL 8B Grasfalt roodwordend | (Ecochain & ACB, 2021) | (NTP, 2024) |
| **Intermediate layer** | **Source** | **Source** |
| AC 16 bind 50% PR | (Ecochain & TNO, 2022) | (Ecochain & TNO, 2022) |
| AC 16 bind 50% PR modified | (Ecochain & TNO, 2022) | (Ecochain & TNO, 2022) |
| AC 16 bind 60% PR Lynpave | (Ecochain & ACB, 2021) | (Asfaltkenniscentrum, 2024) |
| **Base layer** | **Source** | **Source** |
| AC 16 base 50% PR | (Ecochain & TNO, 2022) | (Ecochain & TNO, 2022) |
| AC 16 base 50% PR modified | (Ecochain & TNO, 2022) | (Ecochain & TNO, 2022) |
| AC 16 base 60% PR Lynpave | (Ecochain & ACB, 2021) | (Asfaltkenniscentrum, 2024) |
| AC 16 base 65% PR | (Ecochain & ACB, 2021) | (NTP, 2024) |
| AC 16 base 65% PR Lynpave | (Ecochain & ACB, 2021) | (Asfaltkenniscentrum, 2024) |

# APPENDIX J

*Table J.1: Sources of $CO_2$ emission regarding asphalt mixtures*

| ***Asphalt mixtures*** | ***$CO_2$*** |
|---|---|
| **Top layer** | **Source** |
| AC 11 surf 30% PR | (Ecochain & TNO, 2022) |
| AC 11 surf 30% PR Grasfalt | (Ecochain & ACB, 2021) |
| AC 11 surf 30% PR Lynpave | (Ecochain & ACB, 2021) |
| AC 11 surf 30% PR modified | (Ecochain & TNO, 2022) |
| AC 11 surf NO PR | (Ecochain & TNO, 2022) |
| AC 11 surf tilrood 70/100 3% | (Ecochain & ACB, 2021) |
| Cross planes Possehl | |
| Red Ecofalt | (Ecofalt, 2023) |
| Red layer Possehl | |
| Red wear layer | (Roelofs, 2024) |
| SMA 8-11 | (Ecochain & TNO, 2022) |
| SMA 8-11 modified | (Ecochain & TNO, 2022) |
| SMA 8B 70/100 tilrood 3% | (Ecochain & ACB, 2021) |
| SMA NL 8B Grasfalt | (Ecochain & ACB, 2021) |
| SMA NL 8B Grasfalt roodwordend | (Ecochain & ACB, 2021) |
| **Intermediate layer** | **Source** |
| AC 16 bind 50% PR | (Ecochain & TNO, 2022) |
| AC 16 bind 50% PR modified | (Ecochain & TNO, 2022) |
| AC 16 bind 60% PR Lynpave | (Ecochain & ACB, 2021) |
| **Base layer** | **Source** |
| AC 16 base 50% PR | (Ecochain & TNO, 2022) |
| AC 16 base 50% PR modified | (Ecochain & TNO, 2022) |
| AC 16 base 60% PR Lynpave | (Ecochain & ACB, 2021) |
| AC 16 base 65% PR | (Ecochain & ACB, 2021) |
| AC 16 base 65% PR Lynpave | (Ecochain & ACB, 2021) |

*Table J.2: Sources of $CO_2$ emission regarding machinery*

| **Machinery** | **Source** |
|---|---|
| Asphalt paver 100 kW | (Machineryline, 2024) |
| Asphalt paver 60 kW | (Machineryline, 2024) |
| Emulsion bitumen truck 250 kW | (Machineryline, 2024) |
| Low loader | |
| Milling machine W50 105 kW | (Kempgroep, 2025) |
| Milling machine W100 200 kW | (Kempgroep, 2025) |
| Milling machine W130 240 kW | (Kempgroep, 2025) |
| Mini dumper - Motorjapanner 20 kW | (NIDO, 2017) |
| Mobile crane 150E 115 kW | (SMT, 2025) |
| Mobile crane 160E 105 kW | (SMT, 2025) |
| Mobile sprayer 50 kW | (Bouw Emissie Tool, 2025) |
| Shovel L70 125 kW | (Lectura, 2025) |
| Shovel L90 140 kW | (Lectura, 2025) |
| Site hut | |
| Spreading tractor 60 kW | (GroenKennisNet, 2025) |
| Static roller 25 kW | (Intertechno, 2024) |
| Surface cleaning truck 240 kW | (Appeldoorn, 2024) |
| Sweeper truck 120 kW | (Autoline, 2024) |
| Tack unit 20 kW | (Bouw Emissie Tool, 2025) |
| Tyred roller 60 kW | (Kempgroep, 2025) |
| Tyred roller 90 kW | (Kempgroep, 2025) |
| Vibratory roller 75 kW | (Dynapac, 2025) |
| Vibratory roller 95 kW | (Dynapac, 2025) |
| Watertank | |

*Table J.3: Sources of $CO_2$ emission regarding transport*

| **Transport** | **Source** |
|---|---|
| Passenger car diesel | (Bouw Emissie Tool, 2025) |
| Passenger car gasoline | (Bouw Emissie Tool, 2025) |
| Small bus diesel | (Bouw Emissie Tool, 2025) |
| Small bus gasoline | (Bouw Emissie Tool, 2025) |
| Trailer 400 kW | (Bouw Emissie Tool, 2025) |
| Truck heavy 10x4 600 kW | (Bouw Emissie Tool, 2025) |
| Truck medium 6x6 400 kW | (Bouw Emissie Tool, 2025) |
| Truck medium 8x4 300 kW | (Bouw Emissie Tool, 2025) |

# APPENDIX K

*Table K.1: Sources regarding costs of asphalt mixtures*

| ***Asphalt mixtures*** | ***Costs*** |
|---|---|
| **Top layer** | **Source** |
| AC 11 surf 30% PR | (NTP & ACB, 2024) |
| AC 11 surf 30% PR Lynpave | (NTP & ACB, 2024) |
| AC 11 surf 30% PR modified | (NTP & ACB, 2024) |
| AC 11 surf NO PR | (NTP & ACB, 2024) |
| AC 11 surf tilrood 70/100 3% | (NTP & ACB, 2024) |
| Cross planes Possehl | (Roelofs, 2024) |
| Red Ecofalt | |
| Red layer Possehl | (Roelofs, 2024) |
| Red wear layer | (Roelofs, 2024) |
| SMA 8-11 | (NTP & ACB, 2024) |
| SMA 8-11 modified | (NTP & ACB, 2024) |
| SMA 8B 70/100 tilrood 3% | (NTP & ACB, 2024) |
| SMA NL 8B Grasfalt | (NTP & ACB, 2024) |
| SMA NL 8B Grasfalt roodwordend | (NTP, 2025) |
| **Intermediate layer** | **Source** |
| AC 16 bind 50% PR | (NTP & ACB, 2024) |
| AC 16 bind 50% PR modified | (NTP & ACB, 2024) |
| AC 16 bind 60% PR Lynpave | (NTP & ACB, 2024) |
| **Base layer** | **Source** |
| AC 16 base 50% PR | (NTP & ACB, 2024) |
| AC 16 base 50% PR modified | (NTP & ACB, 2024) |
| AC 16 base 60% PR Lynpave | (NTP & ACB, 2024) |
| AC 16 base 65% PR | (NTP & ACB, 2024) |
| AC 16 base 65% PR Lynpave | (NTP & ACB, 2024) |
| AC 11 surf 30% PR Grasfalt | (NTP & ACB, 2024) |

*Table K.2: Sources regarding costs of asphaltsets*

| ***Asphaltset*** | ***Source*** |
|---|---|
| Asphaltset complete | (NTP, 2023) |
| Asphaltset complete - night | (NTP, 2023) |
| Asphaltset complete - weekend | (NTP, 2023) |
| Asphaltset RZR | (NTP, 2023) |
| Asphaltset RZR - night | (NTP, 2023) |
| Asphaltset RZR - weekend | (NTP, 2023) |
| Asphaltset seamless | (NTP, 2023) |
| Asphaltset seamless - night | (NTP, 2023) |
| Asphaltset seamless - weekend | (NTP, 2023) |
| Cycling path set large | (NTP, 2023) |
| Cycling path set large - night | (NTP, 2023) |
| Cycling path set large - weekend | (NTP, 2023) |
| Cycling path set small | (NTP, 2023) |
| Cycling path set small - night | (NTP, 2023) |
| Cycling path set small - weekend | (NTP, 2023) |
| Handteam | (NTP, 2023) |
| Handteam - night | (NTP, 2023) |
| Handteam - weekend | (NTP, 2023) |
| ***Wear layer set*** | ***Source*** |
| Singular | (NTP, 2023) |
| Sprinkled | (NTP, 2023) |

*Table K.3: Sources regarding costs of machinery*

| ***Machinery*** | ***Source*** |
|---|---|
| Asphalt paver 100 kW | (NTP, 2023) |
| Asphalt paver 60 kW | (NTP, 2023) |
| Emulsion bitumen truck 250 kW | (NTP, 2023) |
| Low loader | (NTP, 2023) |
| Milling machine W50 105 kW | (Aduco, 2024) |
| Milling machine W100 200 kW | (Aduco, 2024) |
| Milling machine W130 240 kW | (Aduco, 2024) |
| Mini dumper - Motorjapanner 20 kW | (NTP, 2023) |
| Mobile crane 150 105 kW | (Van Werven, 2023) |
| Mobile crane 160 115 kW | (Van Werven, 2023) |
| Mobile sprayer 50 kW | (NTP, 2023) |
| Shovel L70 125 kW | (Van Werven, 2023) |
| Shovel L90 140 kW | (Van Werven, 2023) |
| Site hut | (NTP, 2023) |
| Spreading tractor 60 kW | (NTP, 2023) |
| Static roller 25 kW | (NTP, 2023) |
| Surface cleaning truck 240 kW | (Appeldoorn, 2024) |
| Sweeper truck 120 kW | (Appeldoorn, 2024) |
| Tack unit 20 kW | (NTP, 2023) |
| Tyred roller 60 kW | (NTP, 2023) |
| Tyred roller 90 kW | (NTP, 2023) |
| Vibratory roller 75 kW | (NTP, 2023) |

| | |
|---|---|
| Vibratory roller 95 kW | (NTP, 2023) |
| Water tank | (NTP, 2023) |

*Table K.4: Sources regarding costs of transport*

| ***Transport*** | ***Source*** |
|---|---|
| Passenger car diesel | (SIXT, 2024) |
| Passenger car gasoline | (SIXT, 2024) |
| Small bus diesel | (KAV2GO, 2024) |
| Small bus gasoline | (KAV2GO, 2024) |
| Trailer 400 kW | (Van Werven, 2023) |
| Truck heavy 10x4 600 kW | (Van Werven, 2023) |
| Truck medium 6x6 400 kW | (Van Werven, 2023) |
| Truck medium 8x4 300 kW | (Van Werven, 2023) |

*Table K.5: Sources regarding costs of personnel*

| ***Personnel*** | ***Source*** |
|---|---|
| Asphaltcoordinator | (NTP, 2023) |
| Employee | (NTP, 2023) |
| Executor | (NTP, 2023) |
| Finisher | (NTP, 2023) |
| Machinist | (NTP, 2023) |

# APPENDIX L

*Table L.1: Input sensitivity analysis at different percentages for Fill-in sheet*

| Fill-in sheet input parameters | (100%) | (110%) | (90%) |
|---|---|---|---|
| Speed within (km/h) | 40 | 44 | 36 |
| Speed outside (km/h) | 70 | 77 | 63 |
| Speed highway (km/h) | 90 | 99 | 81 |
| Wear layer (m2) | 2500 | 2750 | 2250 |
| Top layer (ton) | 312.5 | 343.75 | 281.25 |
| Intermediate layer (ton) | 312.5 | 343.75 | 281.25 |
| Base layer (ton) | 625 | 687.5 | 562.5 |
| Distance within (km) | 20 | 22 | 18 |
| Distance outside (km) | 60 | 66 | 54 |
| Distance highway (km) | 40 | 44 | 36 |
| **Asphalt mixtures** | | | |
| Wear layer | Red wear layer | | |
| Top layer | SMA NL 8B Grasfalt roodwordend | | |
| Intermediate layer | AC 16 bind 50% PR | | |
| Base layer | AC 16 base 65% PR | | |
| **Asphaltsets** | | | |
| Asphaltset complete | | | |
| Singular | | | |
| **Machinery** | | | |
| Milling machine W100 200 kW | 2022 | | |
| **Transport** | | | |
| Truck heavy 10x4 600 kW | Euro 6 | | |
| **Personnel** | | | |
| Executor | | | |