PAVING THE WAY: STRATEGIC DECISION INDICATORS FOR ROAD ASSET MANAGEMENT

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Note: AI tools are used while making this thesis to translate text from Dutch to English and to improve the readability of the text. The revised text coming from these tools is subsequently checked by the author of this thesis and again adjusted when needed.

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Dear Reader,

Before you lies my Master's Thesis, which marks the conclusion of the Master's program "Civil Engineering and Management" that I have followed over the past two years at the University of Twente. Over the past five months, I delved into the world of asset management. I found it interesting to explore this field and enjoyed all the interviews with the asset managers who were willing to cooperate with my research. Therefore, I would like to thank all the asset managers whom I had the opportunity to interview over the past months.

Conducting this research likely marks the final chapter of my “school years.” Looking back, I realise how much I have learned, both personally and professionally, during the nineteen years I have spent in school. My parents and brothers have been with me throughout this entire journey and have always supported me, for which I am incredibly grateful. I want to thank them for all their help during the writing of this thesis!

Furthermore, I conducted this research in collaboration with the initiative of the Wegverleggers. Personally, I find this an amazing initiative that demonstrates that you can achieve more together than alone, something I have also learned during my time at the University of Twente. I would like to thank the entire Wegverleggers team for all their help and support throughout the process of writing this thesis. In particular, I want to thank Mark Slooijer for all his help and support during the entire research process.

Lastly, I would like to thank my supervisors from the university, Hans Boes and Seirgei Miller. I want to thank them for their guidance and for sharing their knowledge with me in an enthusiastic way.

I wish you a pleasant read.

Kind regards,

Aniek Hollander

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SUMMARY

On average, a Dutch person travels 12,100 kilometres per year on Dutch territory [1]. To facilitate this travel over land, the Netherlands has around 130,000 kilometres of paved roads [2], of which municipalities manage 70% [3]. These municipalities are responsible for maintaining their road networks in good condition [4], while also aligning their strategies with broader (inter)national objectives, such as the Sustainable Development Goals. However, these sustainability goals are relatively new to asset managers and are not yet consistently integrated into their decision-making processes.

Currently, the decision-making process of road asset managers is mainly reactive, relying on CROW guidelines and the implicit knowledge of asset managers. However, there is room for improvement in this decision-making process to ensure that all objectives mentioned in the policy documents, such as sustainability, are systematically considered when making decisions. A standardised set of indicators could support asset managers in making more strategic, goal-oriented decisions, which can help them to reach their goals. Therefore, the main research question of this research is: "*What indicators, data and changes are necessary to assess whether the goals of the asset managers of the future are being met, and to support more strategic decision-making?*".

To answer this research question, qualitative research methods are employed, including desk research reviewing both published and unpublished literature, interviews with asset managers from various municipalities, and a validation workshop involving asset managers, contractors, and an expert from the University of Twente.

In the interviews and desk research, it appeared that asset managers have goals related to, for instance, safety, health, climate adaptation, image, economy, resilience, biodiversity, accessibility, citizen participation, climate neutrality and circularity. In multiple municipalities, a gap is observed between the goals mentioned in policy documents and the focus of asset managers in practice. To reach all strategic goals of the municipalities, this gap needs to be closed. Besides, more indicators and data are needed to make better-argued decisions and to measure whether the goals are reached.

Based on the interviews, it also appeared that asset managers currently mainly take reactive actions when damages to roads occur within the available budget, while it might be beneficial for asset managers to take more proactive actions when municipalities want to achieve all their goals. Making this shift towards more proactive strategies requires additional and more detailed data.

Some of the interviewees mentioned the need for more detailed data and indicators on the severity and location of road damage to enable the development of more effective maintenance strategies and to gain deeper insights into road deterioration, which is needed to move toward predictive road maintenance. Currently, most asset managers rely on the CROW visual inspection guideline to assess the condition of their roads. However, the interviews suggest that these inspections are not always sufficiently detailed and involve a degree of subjectivity. This finding was validated during the validation workshop.

Additionally, to reach the regional and (inter)national goals related to circularity, data on material flows and the application of circularity principles in decision-making of asset managers are essential for monitoring the level of circularity achieved in infrastructure projects. To identify which data and indicators are needed to effectively measure and implement circularity in asset management, a clear and commonly accepted definition of circularity is necessary. Currently,

asset managers appear to lack such a shared understanding, which limits the implementation of circularity in practice.

Moreover, data and indicators are needed to measure climate neutrality to reach the sustainability goals of the Netherlands. For each decision that an asset manager makes, it needs to be calculated which impact it has on the greenhouse gas emissions of CO_2, CH_4, N_2O, HFK, SF_6 and PFKs. To incorporate climate neutrality more effectively into the decision-making process of asset managers, a clear definition and measurable goal must be established for climate neutrality. Many asset managers indicated that current climate neutrality goals are not always well understood, which limits the realisation of these goals in practice. To address this, a uniform method and indicator should be developed for climate neutrality.

As climate change progresses, climate adaptation is also becoming an increasingly important consideration for asset managers. Although no specific indicators for climate adaptation could be identified, given its dependency on various factors, the interviews suggest that asset managers should assess climate-related risks during the decision-making process and select options that best address these risks. These climate-related risks are related to aspects such as extreme drought, rainfall, and heat. This requires a long-term perspective and a decision about which climate-related damages the municipality is willing to accept, a concept referred to as “climate acceptance”. Currently, many municipalities appear to lack such a long-term perspective.

Lastly, greater insight is needed into both the product and process quality of asphalt roads. Identifying risk areas in the pavement enables asset managers to incorporate this knowledge into their maintenance strategies. Understanding the initial road quality can support better predictions of the deterioration of roads, which in turn facilitates preventive maintenance.

SAMENVATTING

Een Nederlander legt gemiddeld 12.100 kilometer per jaar af binnen het Nederlandse grondgebied [1]. Om dit vervoer over land mogelijk te maken, beschikt Nederland over ongeveer 130.000 kilometer aan verharde wegen [2], waarvan 70% wordt beheerd door gemeenten [3]. Deze gemeenten zijn verantwoordelijk voor het in goede staat houden van hun wegennetwerk [4], terwijl ze ook rekening moeten houden met bredere (inter)nationale doelstellingen, zoals de Sustainable Development Goals. Deze duurzaamheidsdoelen zijn echter relatief nieuw voor assetmanagers en worden nog niet consequent geïntegreerd in hun besluitvormingsprocessen.

Op dit moment is het besluitvormingsproces van assetmanagers voornamelijk reactief, gebaseerd op de CROW-richtlijnen en de impliciete kennis van assetmanagers. Er is echter ruimte voor verbetering in dit besluitvormingsproces zodat alle doelstellingen uit de beleidsdocumenten, zoals duurzaamheid, systematisch worden meegenomen in de besluitvorming. Een gestandaardiseerde set indicatoren kan assetmanagers ondersteunen bij het maken van strategischere, doelgerichte keuzes, en zo helpen bij het behalen van hun doelstellingen. Daarom luidt de hoofdvraag van dit onderzoek: "*Welke indicatoren, data en veranderingen zijn nodig om te beoordelen of de doelen van de assetmanager van de toekomst worden behaald, en om strategischere besluitvorming te ondersteunen?".*

Om deze onderzoeksvraag te beantwoorden, worden er kwalitatieve onderzoeksmethoden toegepast, waaronder literatuur onderzoek waarin er wordt gekeken naar zowel gepubliceerde als niet-gepubliceerde documenten, interviews met assetmanagers uit verschillende gemeenten, en een validatieworkshop met assetmanagers, aannemers en een expert van de Universiteit Twente.

Uit de interviews en het literatuuronderzoek blijkt dat assetmanagers doelstellingen hebben op het gebied van onder andere veiligheid, gezondheid, klimaatadaptatie, imago, economie, biodiversiteit, toegankelijkheid, burgerparticipatie, klimaatneutraliteit en circulariteit. In meerdere gemeentes is er een kloof zichtbaar tussen de doelstellingen benoemd in beleidsdocumenten en de focus van assetmanagers in de praktijk. Om alle strategische doelstellingen van gemeentes te realiseren, moet deze kloof worden overbrugd. Daarnaast zijn er meer indicatoren en gegevens nodig om beter onderbouwde besluiten te kunnen nemen en om te meten of de doelstellingen van gemeentes worden behaald.

Uit de interviews komt ook naar voren dat assetmanagers momenteel vooral reactief handelen, binnen het beschikbare budget, wanneer er schade aan wegen optreedt, terwijl het voor het behalen van alle gemeentelijke doelen juist gunstig zou kunnen zijn als zij proactiever te werk zouden gaan. Deze verschuiving naar een proactievere aanpak vereist aanvullende en gedetailleerdere data.

Enkele geïnterviewden gaven aan dat er behoefte is aan gedetailleerdere data en indicatoren over de ernst en locatie van wegschades. Dit is nodig om effectievere onderhoudsstrategieën te ontwikkelen en om beter inzicht te krijgen in het verloop van wegveroudering, wat essentieel is om te weten voor de overstap naar voorspellend onderhoud. Momenteel maken de meeste assetmanagers gebruik van de visuele globale inspectie van CROW om de conditie van hun wegen in kaart te brengen. Uit de interviews blijkt echter dat deze inspecties niet altijd gedetailleerd genoeg zijn en een zekere mate van subjectiviteit bevatten. Deze bevinding is gevalideerd in de validatie workshop.

Daarnaast is er, om de regionale en (inter)nationale doelstellingen op het gebied van circulariteit te behalen, data over materiaalstromen en de toepassing van circulariteitsprincipes in het

besluitvormingsproces van assetmanagers essentieel om de mate van circulariteit in infrastructuurprojecten te monitoren. Om vast te stellen welke data en indicatoren er nodig zijn om circulariteit effectief te meten en te implementeren in assetmanagement, is er een duidelijke en uniforme definitie van circulariteit nodig. Momenteel lijken de asset managers geen duidelijke en uniforme definitie van circulariteit te hebben, wat de implementatie ervan in de praktijk belemmert.

Verder zijn er data en indicatoren nodig om klimaatneutraliteit te meten om de duurzaamheidsdoelstellingen van Nederland te behalen. Bij elke beslissing die een assetmanager maakt, moet er worden berekend wat de impact ervan is op de uitstoot van broeikasgassen zoals CO_2, CH_4, N_2O, HFK, SF_6 en PFK's. Om klimaatneutraliteit effectiever te integreren in het besluitvormingsproces van assetmanagers, is er een heldere definitie en een meetbaar doel nodig voor klimaatneutraliteit. Veel assetmanagers geven aan dat de huidige doelen voor klimaatneutraliteit niet altijd duidelijk zijn, wat de praktische uitvoering ervan belemmert. Om dit aan te pakken, zou er een uniforme methode en indicator voor klimaatneutraliteit moeten worden ontwikkeld.

Naarmate de klimaatverandering voortschrijdt, wordt klimaatadaptatie ook een steeds belangrijker aandachtspunt voor assetmanagers. Hoewel er geen specifieke indicatoren voor klimaatadaptatie konden worden vastgesteld, omdat dit afhankelijk is van diverse lokale factoren, blijkt er uit de interviews dat assetmanagers klimaat gerelateerde risico's zouden moeten beoordelen tijdens het besluitvormingsproces en keuzes zouden moeten maken die deze risico's zo ver mogelijk beperken. Deze risico's hebben te maken met onder andere extreme droogte, neerslag en hitte. Dit vereist een langetermijnvisie van assetmanagers en een duidelijke beslissing over welke klimaatschade een gemeente bereid is te accepteren, een concept dat ook wel wordt aangeduid als "klimaatacceptatie". Momenteel lijken veel assetmanagers zo'n langetermijnperspectief te missen.

Tot slot is er meer inzicht nodig in zowel de product- als productiekwaliteit van asfaltwegen. Het identificeren van mogelijke zwakke plekken in het wegdek stelt assetbeheerders in staat om deze kennis te verwerken in hun onderhoudsstrategieën. Inzicht in de initiële wegkwaliteit kan bovendien helpen bij het beter voorspellen van wegveroudering, wat preventief onderhoud vergemakkelijkt.

ACRONYMS

CO_2	Carbon dioxide
CROW	Centrum voor Regelgeving en Onderzoek in de Grond-, Water-, en Wegenbouw en de Verkeerstechniek (In English: Centre for Regulation and Research in Ground, Water, Road and Traffic Engineering)
HMA	Hot Mix Asphalt
IRI	International Roughness Index
MCI	Material Circularity Indicator
MKI	Milieu Kosten Indicator (in English: Environmental Cost Indicator)
MPD	Mean Profile Depth
N_2	Nitrogen
PCI	Pavement Condition Index
PCR	Product Category Rules
PSI	Pavement Serviceability Index
SAMP	Strategic Asset Management Plan
SDG	Sustainable Development Goals
SMART	Specific, Measurable, Achievable, Relevant and Time-bounded
WMA	Warm Mix Asphalt

NOTE: In this context, the term 'asset managers' refers specifically to the asset managers of municipalities in the Netherlands, unless stated otherwise.

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1 INTRODUCTION

Infrastructure is essential to society [5], encompassing roads, bridges, water pipes, and electricity grids. In 2023, residents of the Netherlands aged six years or older travelled 199.3 billion kilometres on Dutch territory [1]. That is an average travel distance of over 12.1 thousand kilometres per year per inhabitant in the Netherlands [1]. Furthermore, land transport also contributed 1.7% to the Dutch economy in 2023 [6]. This shows the importance of land transport infrastructure to Dutch society.

To facilitate this land transport, the Netherlands has approximately 130,000 kilometres of asphalt roads [2], of which around 18% are managed by Rijkswaterstaat, 12% by provinces, and 70% by municipalities [3]. According to Dutch law (article 16 of the "Wegenwet"), municipalities are responsible for ensuring that roads within their area, except for those managed by Rijkswaterstaat or the province, are maintained in good condition [4]. Achieving this requires effective infrastructure asset management. According to Too (2010) [7], infrastructure asset management is "a strategic and systematic process of optimising decision-making in resources allocation with the goal of achieving planned alignment of an infrastructure asset with corporate goals throughout its lifecycle" [7].

A major challenge in infrastructure asset management is the maintenance of ageing infrastructure. Much of Europe's public infrastructure, such as roads and bridges, was built shortly after World War II and now requires extensive maintenance [8]. Asset managers must keep infrastructure in good condition while operating within budget constraints. At the same time, they must also address broader (inter)national goals, such as achieving CO_2 neutrality and establishing a fully circular economy by 2050 [9] [10]. To reach these goals, the way of working has to change in the infrastructure sector, which is responsible for high amounts of greenhouse gas emissions (2 Mt CO2 equivalents per year in the Netherlands [11]).

Currently, infrastructure asset managers in the Netherlands seem to make decisions largely based on their own implicit knowledge, which is usually still based on technical parameters and does not always consider sustainability aspects. There does not seem to be a standard decision-making process, which includes indicators related to sustainability, used by every asset manager in the Netherlands to make the most strategic decisions. The only standardised indicators used in the Netherlands are the CROW indicators, which are focused on the technical properties of a road [12]. Establishing a standardised set of indicators that reflects all the objectives of asset managers could support more strategic, data-driven decision-making, thereby enabling them to achieve their broader ambitions.

This study therefore aims to answer the following research question: *What indicators, data and changes are necessary to assess whether the goals of the asset managers of the future are being met, and to support more strategic decision-making?*. To answer this question, qualitative research methods are employed, including desk research, semi-structured interviews and a validation workshop.

The structure of this report is as follows. Chapter 2 introduces the problem statement, research objective, and research question, as well as the scope of the study. Subsequently, Chapter 3 explores background literature, offering insight into the context in which asset managers operate and the policy objectives they must consider in their decision-making. Next, Chapter 4 presents the research methodology. Furthermore, Chapters 5, 6 and 7 outline the main results of the study, followed by a discussion in Chapter 8. Building on these insights, Chapter 9 provides recommendations. Finally, a conclusion is given in Chapter 10.

2 Problem Statement, research objective, research questions and scope

In this chapter, the problem statement, research objective, research questions and scope are discussed. In Section 2.1, the problem statement is described. Subsequently, the research objectives and research questions are derived from the problem statement in Sections 2.2 and 2.3, respectively. Furthermore, the scope of the study is also discussed in Section 2.4.

2.1 Problem Statement

The problem addressed in this thesis can be characterised as a wicked problem. A wicked problem is a problem with no clear solution, which is unique and on which the solutions are not true-or-false, but rather good-or-bad [13]. The information needed to understand the problem depends on someone's idea for solving it [13].

The wicked problem explored in this thesis concerns the decision-making process of infrastructure asset managers. Infrastructure asset managers are increasingly faced with a growingly complex task in maintaining and managing infrastructure. While the traditional focus has been on technical quality and cost-efficiency, asset managers are now expected to integrate a broader range of sustainability objectives, such as those outlined in the Sustainable Development Goals [14], into their strategic considerations, which complicate their decision-making process. The effects of climate change and the finite availability of materials require the integration of goals such as circularity, climate adaptation, and climate neutrality into the decision-making processes of asset managers [10] [15]. Additionally, several other challenges are expected to impact infrastructure asset management, such as budget constraints, increasing demand, ageing infrastructure, rising societal expectations, human development, and infrastructure interdependencies [5].

From conversations with asset managers of municipalities, it appears that asset managers often make decisions based on their implicit knowledge, which is usually still based on technical parameters and does not always consider other aspects such as sustainability. There does not seem to be a standard decision-making process with comprehensive indicators, including sustainability indicators, used by every asset manager in the Netherlands to make the most strategic decisions. Besides, in the literature, almost nothing can be found on standard indicators used by asset managers in the Netherlands to base decisions on. The only standardised indicators used in the Netherlands are the CROW indicators, which are focused on the technical properties of a road [12].

To make better strategic choices as an asset manager, it could be useful to have a standard and comprehensive set of indicators based on which choices can be made. Such a standard and comprehensive set of indicators does not exist yet, and it is questionable which indicators should be included to capture all the goals of asset managers. Therefore, this research examines which indicators, data and changes are needed to improve the decision-making process of asset managers in the Netherlands. This information can help asset managers of municipalities to optimise their decision-making process to reach all their ambitious goals that benefit society.

2.2 Research Objective

The research objective is to create insight into which indicators, data and changes are needed in the field of asset management to make more strategic decisions about the management of municipal asphalt roads. The objective is to create insight into how better strategic decisions can be made by analysing which indicators, data, and changes are relevant for asset managers to make strategic decisions. The aim is to analyse this by conducting a literature review, as well as interviews and a workshop with asset managers.

2.3 Research Questions

The main research question is derived from the problem statement and the research objective. The main research question is as follows:

Main question

What indicators, data and changes are necessary to assess whether the goals of the asset managers of the future are being met, and to support more strategic decision-making?

Subsequently, four sub-questions are defined to answer the main research question. After answering these four sub-questions, an answer can be given to the main question. Note that the problem dealt with in this research is a wicked problem, so the answers to these questions are not true-or-false but rather good-or-bad [13]. The four sub-questions are:

Sub-question 1

What are the client/asset manager's goals in general and concerning 2030 -2050?

Sub-question 2

How do asset managers currently make decisions and integrate policy goals, data, and indicators into their daily practice?

Sub-question 3

Which indicators and data are considered relevant according to the literature and asset managers for making more optimal asset management decisions and determining whether the objectives of the client/asset manager are being achieved?

Sub-question 4

Which changes to current asset management practices can support more strategic decision-making by future asset managers?

2.4 Scope

The impetus for this study is an initiative called "Wegverleggers". The Wegverleggers is an initiative of the municipalities of Enschede and Losser, along with NTP and Roelofs. These parties are collaborating over a long period, up to eight years, with the main purpose of carrying out major maintenance on asphalt roads within the municipalities of Losser and Enschede [9].

The aim of this initiative goes beyond the traditional way of road maintenance. The purpose of this collaboration is also to develop, learn, and innovate to achieve all the municipalities' goals and ambitions [9]. The underlying objectives of this initiative include increasing integrated developments, becoming CO_2 neutral by 2050, creating a healthy and climate-adaptive living environment, and achieving full circularity by 2050 [9].

Additionally, this collaboration aims to implement data-driven asset management to enable asset managers to reach the earlier-mentioned objectives [9]. Furthermore, these parties seek to share knowledge both internally and externally [9]. External parties can also become "Wegverleggers" and, in doing so, contribute to knowledge sharing.

This thesis supports the goals of the Wegverleggers by providing insights into the need for indicators, data, and necessary changes to optimise the decision-making process of asset managers such that the goals of municipalities can be met to a higher extent. Creating insight into these elements can help the Wegverleggers to identify steps that they can take to improve the decision-making process of asset managers.

Since the initiative of the Wegverleggers is related to municipal roads, this research focuses on municipal road asset management in the Netherlands. It does not explicitly consider other infrastructure assets such as bridges, water pipelines, or the electricity grid. Besides, it is chosen to focus on asphalt roads and not on element paving, since most improvements can probably be made in the field of asphalt paving. Highways and provincial roads also fall outside the scope of this study since these roads are usually used more intensively and therefore require other management strategies. However, the working practices of provinces are used as inspiration in this research.

3 BACKGROUND LITERATURE

This chapter reviews relevant literature to provide insight into the context in which asset managers operate and the policy objectives they must consider in their decision-making process. First, it explains the life cycle of asphalt roads in the Netherlands (see Section 3.1). Next, it explores the policy objectives that influence asset management decisions (see Section 3.2). Finally, it discusses how infrastructure asset management is currently approached according to the literature (see Section 3.3).

3.1 ASPHALT ROADS IN THE NETHERLANDS

In the Netherlands, there are approximately 130,000 kilometres of asphalt roads [2], of which around 18% are managed by Rijkswaterstaat, 12% by provinces, and 70% by municipalities [3]. In Figure 1, it is shown which roads around Losser and Enschede are, for instance, owned by the national road authority, the province and the municipality [16]. These roads are composed of multiple asphalt layers, each serving a different function [17]. The main components of asphalt include sand, aggregates, filler, and bitumen [2] [17]. With these 'ingredients', different types of asphalt can be made such as very open asphalt concrete (ZOAB), where more than 80% of the national roads in the Netherlands are made of [2]. Furthermore, dense asphalt concrete (AC) and stone-mastic asphalt (SMA), for example, can also be made from these 'ingredients' [2].

There is an increasing focus on developing more sustainable and environmentally friendly asphalt mixtures in which, for instance, bitumen is replaced by bio-based materials such as lignin, which is a material produced from grass [2] [18]. Besides, more and more asphalt is recycled in the Netherlands, with as benefit that an asphalt mixture that incorporates reclaimed asphalt includes less bituminous binder and virgin aggregates compared to conventional asphalt mixtures [19].

Traditionally, asphalt production involved heating the materials to temperatures of around 150-190°C, known as hot mix asphalt (HMA) [20]. Since January 1, 2025, warm mix asphalt (WMA) has become the standard in the Netherlands, requiring lower production temperatures of 100-140°C [20] [21]. In 2020, approximately 7.1 million tonnes of WMA and HMA were produced in the Netherlands [17].

Figure 1 - Responsible road authorities of roads near Enschede and Losser [16]

The life cycle of asphalt roads consists of several phases: the design phase, the construction phase, the use phase, and the end-of-life phase (see Figure 2). The following sections explain each phase in more detail.

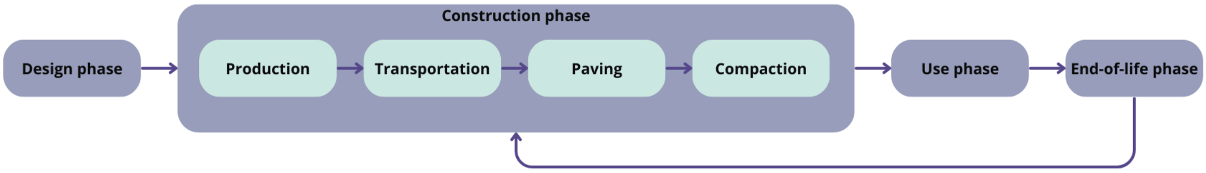

Figure 2 - Lifecycle of asphalt roads

3.1.1 The design phase

First of all, a road has to be designed before it can be built. In road construction, traditional forms of contracts are still often used where the design phase is the responsibility of the client [22]. This traditional way of working, where there is a separation between the design and construction phases, causes innovations to be hampered [22]. Since the most can be achieved in the preliminary phase of a project [22]. The choices made in this preliminary phase also influence the subsequent phases.

The literature identifies several dimensions that are important for construction projects in general and are therefore also important to consider in the design process of asphalt roads. According to Fewings and Henjewele (2019), three dimensions are important in a project and should be weighed against each other; time, quality and cost [23]. However, an article on the design of housing projects mentions that nowadays, the environment and society are also important aspects to consider if a project is to be a success [24].

3.1.2 The construction phase

After the design is made for a road and the tender is done, the construction phase of the road can begin. The asphalting process can be divided into four phases: the production phase, the transport phase, the paving phase and the compaction phase [25] [26]. These four phases must be coordinated to avoid discontinuities in the asphalting process that may lead to variability and thus lower quality of the final compacted asphalt layer [27].

The quality of an asphalt road that is reached during the construction of the road depends on the density that is reached during compaction [28]. The asphalt density is mainly dependent on compaction operations [25] [26] and the asphalt temperature at which compaction occurs [25] [26]. The temperature should be as homogeneous as possible during compaction to reach the highest possible quality [26] and the compaction should be homogeneous, avoiding over- or undercompaction [26]. Other factors that influence compaction are environmental conditions (e.g. ambient air temperature, wind speed or rainfall) and material properties [28]

3.1.3 The use phase

During the use phase of asphalt roads, roads age due to exposure to air, UV radiation, water and dirt [2]. How fast roads age depends on the process quality and product quality achieved in the construction phase [17]. Furthermore, it also depends on other factors such as environmental factors and traffic load [17]. The life cycle of asphalt roads can be extended by using self-healing asphalt or rejuvenating cream [3].

To evaluate the pavement conditions during the use phase, it is crucial to assess the following technical parameters: transverse evenness, longitudinal evenness, surface texture, friction, cracking, other surface defects and bearing capacity [29] [30]. These technical parameters give insight into the performance of asphalt roads.

Two types of indicators can be used to measure the performance of roads: functional and structural indicators [29]. The functional indicators relate to the ride quality and safety of the asphalt pavement, and the structural indicators refer to the ability of the pavement to withstand traffic load [29]. According to Marcelino et al. (2017), both types of indicators are important to assess the performance of the asphalt road, and in the ideal situation, there would be comprehensive performance indicators that could express all this information [29]. However, Marcelino et al. (2017) argue that collecting all data needed for these indicators is expensive, so a balance needs to be made in what data is essential to collect and the costs [29].

3.1.4 End-of-life phase road

At end-of-life, the road materials can be reused as recycled material in new asphalt roads, as asphalt is easily recyclable except for old tar holding asphalt [31]. The advantage of using reclaimed asphalt in new asphalt mixtures is that less bituminous binder and new aggregates are required compared to conventional asphalt mixtures [19].

Furthermore, pilot projects are currently being done with the asphalt recycling train (ART) initiated by Rijkswaterstaat. This technology allows old asphalt at the end of its service life to be converted into new asphalt on-site [32]. However, not much can currently be found about the success of these pilot studies, and monitoring is needed to determine the effects of the Asphalt Recycling Train on the asphalt's lifespan [33].

3.2 ROAD MAINTENANCE POLICIES

As indicated in Section 3.1, about 18% of roads are managed by Rijkswaterstaat, 12% by provinces and 70% by municipalities [34]. Each road authority has its own policy when it comes to asset management, although there is considerable overlap in the objectives that road authorities have, as they all have to take into account nationally formulated objectives and legislation.

In this section, an explanation is provided regarding the findings in both published and unpublished documents about the objectives of road authorities. Important sources from which these objectives were derived include the document "Roadmap Transitiepad Wegverharding" created by Rijkswaterstaat, as well as policy documents and enquiry documents from road authorities [34] [35] [9] [36] [37]. The "Roadmap Transitiepad Wegverharding" was developed by Rijkswaterstaat and NewForesight to provide direction for achieving climate and circularity goals [34]. Other documents indicate that in projects also other objectives beyond climate and circularity have to be considered, such as social, economic, and quality-related goals [37] [9] [36] [38]. This section further elaborates on all these objectives. In Figure 1, a list of identified goals in the literature is given.

3.2.1 Environmental goals

Currently, there are major landscape-level issues, such as climate change and the limited amount of materials on earth, that are putting pressure on the asphalt sector. The European Environment Agency (EEA) indicates that climate change will have a major impact on people's daily lives by increasing the likelihood of, for example, floods, droughts and heat waves [39]. Moreover, the EEA stresses that Europe is insufficiently prepared for these climate risks [39] [40]. Because of these landscape-level problems, there are ambitious international climate goals that are further elaborated on at national, regional and local levels. To achieve these goals, ways of working have to change in, for example, the infrastructure sector, which is responsible for a large amount of greenhouse gas emissions (2 Mt of CO_2 equivalents per year in the Netherlands [11]).

Road authorities in the Netherlands currently have various objectives they aim to achieve regarding topics such as climate, biodiversity, sustainability, and circularity [34] [40] [10] [37] [35]. These objectives align with international goals, such as the Sustainable Development Goals (SDGs) and the Paris Agreement [14]. In road construction, SDG 9 ("Industry, Innovation, and Infrastructure"), SDG 11 ("Sustainable Cities and Communities"), and SDG 12 ("Responsible Consumption and Production") are particularly important [14]. These international goals have been translated into the objectives of the European Union [41], which have subsequently been further adapted at the national level.

For example, all EU countries are legally required to combat climate change by becoming climate-neutral by 2050 [42]. This goal has therefore been incorporated into the national objectives of the Netherlands and the policy documents of all road authorities in the country [43]. Additionally, the Dutch government aims to establish a fully circular economy by 2050, a goal that is also reflected in regional and local policy documents [34] [40] [10] [37] [35]. As an interim target, the Netherlands aims to reduce the use of primary raw materials by 50% by 2030 [10].

To achieve this goal, increasing circularity in the construction sector is important. Currently, the construction sector is responsible for 50% of raw material consumption, 40% of total energy use, and 30% of total water consumption in the Netherlands [10]. Additionally, 40% of the waste in the Netherlands comes from construction and demolition waste, and the construction sector accounts for approximately 35% of CO_2 emissions [10]. The Dutch government's circular vision for the construction sector is as follows (translated from Dutch[1]) [10]:

"By 2050, the construction sector will be organised in such a way that, throughout the design, development, use, management, and dismantling phases, structures are built, reused, maintained, and deconstructed sustainably. Sustainable materials will be used in construction, and the evolving wishes of users will be taken into account. The goal is to achieve an energy-neutral built environment by 2050, in compliance with the European agreements. Wherever possible, structures will make use of ecosystem services (natural capital, such as the water retention capacity of the subsoil)"

This means that sustainability should be included in all the life cycle stages of an object. Several initiatives have been set up nationally and internationally to make this circular vision a reality. First of all, a project called CERCOM (Circular Economy in Road COnstruction and Maintenance) has been launched which is funded by Denmark, Ireland, the Netherlands, Norway, Sweden, Switzerland and the United Kingdom [44]. This project aims to provide tools and supporting resources to national road authorities to support the transition to a circular economy [44]. Furthermore, the platform CB'23, which stands for Circular Building in 2023, was established in 2018 by Rijkswaterstaat and by Rijksvastgoedbedrijf supported by the Bouwcampus and the NEN. Subsequently, other parties also joined this initiative, which aims to reach nationally supported agreements on circular construction before 2023 [45].

Additionally, there are specific targets in the Netherlands related to greenhouse gas emissions. The goal is to reduce the emissions of greenhouse gases by 95% compared to 1990 by 2050 in the Netherlands [43]. To achieve this, road authorities aim to completely eliminate greenhouse gas emissions on construction sites and reduce emissions from mobile machinery and construction

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[1] Dutch version: *"In 2050 is de bouw bij ontwerp, ontwikkeling, gebruik, beheer en demontage van bouwwerken zo georganiseerd dat deze objecten duurzaam worden gebouwd, (her)gebruikt, onderhouden en ontmanteld. Bij bouwen wordt gebruik gemaakt van duurzame materialen en wordt aangesloten bij de dynamische wensen van de gebruikers. Het streven is naar een energie neutrale gebouwde omgeving in 2050 conform de Europese afspraken. Bouwwerken maken zoveel mogelijk gebruik van ecosysteemdiensten (natuurlijk kapitaal zoals het waterbergend vermogen van de ondergrond)."* [10]

transport [9] [35]. Furthermore, reducing energy consumption during asphalt production is important for road authorities, as 26% of the greenhouse gas emissions in the asphalt supply chain come from the asphalt production process [34]. Moreover, there is an ambition to replace bitumen, which is currently used as a binder material, with bio-based alternatives. Road authorities also aim to extend the lifespan and improve the quality of asphalt [34] [40] [9] [37]. In addition to phasing out abiotic materials, road authorities try to create a climate-adaptive living environment [9] [36] [37].

It becomes more and more important to create a climate-adaptive living environment since the climate is changing rapidly, leading to higher temperatures, more extreme rainfall, prolonged droughts, and rising sea levels [15]. In the Netherlands, the average temperature has increased by 1.8°C since 1900 [15]. Additionally, the annual rainfall increased by 27% between 1910 and 2015 [15], while the intensity of heavy rainfalls, causing water-related issues, has increased by 20% [15]. These trends in temperature rise, changing precipitation patterns, droughts, and sea-level rise are expected to continue in the coming years [15] [46]. Therefore, the goal of many road authorities is to become climate-adaptive so that they are prepared for this climate change [9] [47].

3.2.2 Innovation and Knowledge Sharing

To achieve the goals related to circularity, sustainability, and climate, as mentioned in Section 3.2.1, innovation is important [34] [37] [9]. Therefore, some road authorities aim to stimulate innovation [34] [9]. Knowledge sharing and collaboration play a crucial role in this process of stimulating innovation. As a result, some road authorities have also set the goal of increasing knowledge sharing and collaboration to support innovation [9]. Additionally, some of them are increasingly focusing on data-driven maintenance [9].

Moreover, some municipalities aim to implement integral developments [26], meaning that projects are planned and developed in a broader, interconnected manner rather than in isolation. The advantage of this working method is that it allows for better learning between projects, making it easier to scale up innovations. This working method should also help to reduce the average cost per project.

3.2.3 Social goals

Furthermore, road authorities have various social objectives. For example, the motto of Rijkswaterstaat is (translated from Dutch[2]): “Working together for a safe, liveable and accessible Netherlands. That is Rijkswaterstaat” [38]. This motto clearly emphasises that safety is a main priority for road authorities [9] [38] [37]. Moreover, policy documents from municipalities indicate that social aspects such as a healthy living environment, accessibility, and comfort are also important goals for road authorities [9].

The participation of residents, businesses, and institutions is also essential for road authorities to ensure the success of a project [9] [36]. After all, one of the main goals of road authorities is to ensure citizen satisfaction [36]. To achieve this, transparency in road paving projects is also necessary [9].

3.2.4 Economic goals

Economic objectives are also important for road authorities. They aim to work as cost-efficiently as possible and minimise transaction costs [9] [37]. Additionally, for road authorities such as

[2] Dutch version: Samen werken aan een veilig, leefbaar en bereikbaar Nederland. Dat is Rijkswaterstaat. [38]

municipalities, it is important that their projects contribute to stimulating the local economy and creating job opportunities [9].

Figure 3 - Goals of road agencies according to policy documents

3.3 Infrastructure asset management

To reach the goals of road authorities mentioned in Section 3.2, it is important for asset managers to make strategic decisions. This section first explains how the need for good infrastructure is increasing (see Section 3.3.1). Furthermore, the current practice of infrastructure asset management is explained in this section (see Section 3.3.2), and it is discussed which data and indicators can be used according to the literature for infrastructure asset managers to make strategic decisions (see Section 3.3.3).

3.3.1 The need for infrastructure asset management

Infrastructure is essential to society [5], encompassing roads, bridges, water pipes, and electricity grids. In 2023, residents of the Netherlands aged six years or older travelled 199.3 billion kilometres on Dutch territory [1]. That is an average travel distance of over 12.1 thousand kilometres per year per inhabitant in the Netherlands [1]. Furthermore, land transport also contributed 1.7% to the Dutch economy in 2023 [6]. Recognising the importance of infrastructure, one of the Sustainable Development Goals (SDG 9.1) aims to "develop quality, reliable, sustainable, and resilient infrastructure, including regional and transborder infrastructure, to support economic development and human well-being, with a focus on affordable and equitable access for all" [14].

Much of Europe's public infrastructure, such as roads and bridges, was built shortly after World War II and now requires extensive maintenance [8]. How can infrastructure owners ensure these structures remain reliable, safe, and cost-efficient? This is where infrastructure asset management plays an important role.

According to Too (2010) [7], infrastructure asset management is "a strategic and systematic process of optimising decision-making in resources allocation with the goal of achieving planned alignment of an infrastructure asset with corporate goals throughout its lifecycle" [7]. Managing infrastructure is a complex, multi-dimensional task that involves considerations from various fields, including management, engineering, economics, and sociology [5].

Additionally, several challenges are expected to impact infrastructure asset management, such as budget constraints, increasing demand, ageing infrastructure, rising societal expectations, climate change, sustainability concerns, human development, and infrastructure interdependencies [5].

3.3.2 Current practice infrastructure asset management for roads

The Netherlands has approximately 130,000 km of asphalt roads [2], with management responsibilities divided among different authorities: around 18% of the roads are managed by Rijkswaterstaat, 12% by provinces, and 70% by municipalities [3]. According to the law, municipalities have to ensure that roads in their area are in good condition. Article 16 of the 'wegenwet' mentions the following about the role of municipalities as infrastructure asset managers for roads (translated from Dutch[3]) [4]:

"The municipality has to ensure that the roads within its area, with the exception of the roads maintained by the state or a province, those referred to in Article 17 and those on which tolls are levied by another party, with the exception of the municipal roads listed in the appendix to the Wet vrachtwagenheffing, are in good condition."

Therefore, indicators are needed to determine if roads are in good condition. The most frequently referenced sources in policy documents of asset managers that include indicators to measure the technical quality of roads are CROW publications 146 and 147 [48] [12] [49]. These documents are cited in several municipal road policy plans. These CROW documents outline methods for assessing road quality and provide guidance on maintenance strategies based on the condition of the roads.

Beyond the technical quality of roads, municipalities also set objectives related to safety, health, climate adaptation, image, economy, resilience, biodiversity, accessibility, citizen participation, and sustainability in their road policies [50] [51] [52] [53]. Indicators are needed to measure progress toward reaching these goals. Many road policy documents do not specify indicators to measure all these goals. The indicators that are mentioned in the policy document mainly focus on the technical condition of roads, which can be related to goals such as safety, appearance, durability, and comfort [12]. However, indicators for assessing aspects like circularity in road infrastructure are often absent from the policies reviewed in this literature study.

Policy documents also show the challenges municipalities face in prioritising road maintenance due to budget constraints [50] [51] [52]. Each municipality prioritises which roads require maintenance at a given time, but there appears to be no standardised method for prioritisation. Approaches seem to vary across municipalities when looking at the policy documents. However, it is observed in the policy documents that often, safety has the highest priority. Furthermore, it is seen in some policy documents that the type of road and the location of the roads play an important role in the prioritisation of the roads.

Moreover, it could be found in the literature that much data is experienced in the minds of the asset managers but is not factually recorded [54]. It appears that municipalities' choices regarding road asset management are often mainly determined by the implicit knowledge of asset managers. However, it is not completely clear exactly what knowledge asset managers use to make choices.

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[3] Dutch version: *De gemeente heeft te zorgen, dat de binnen haar gebied liggende wegen, met uitzondering van de wegen, welke door het Rijk of eene provincie worden onderhouden, van die bedoeld in artikel 17 en van die, waarop door een ander tol wordt geheven met uitzondering van de gemeentelijke wegen, genoemd in de bijlage bij de Wet vrachtwagenheffing, verkeeren in goeden staat.* [4]

Therefore, this research includes interviews to try to create more insight into this knowledge (see Chapter 5).

Besides, the CROW did set up the iAMPro model as a guideline for asset managers [55]. Figure 4 visualises the iAMPro model, which comprises three components: process stages, data & information, and human & organisation [55]. In this model, data, information, human, and organisational aspects serve as preconditions for successfully executing the process stages [55]. The model also integrates the Plan-Do-Check-Act (PDCA) cycle. This continuous cycle involves:

- Planning activities (Plan);
- Executing planned actions (Do);
- Critically reviewing outcomes and performance (Check);
- Implementing improvements where necessary (Act).

In the iAMPRo model, asset managers are mainly responsible for tactical-level tasks [47]. Their role involves the management of assets and programming asset management plans. They are also responsible for planning and preparing measures for the assets. Besides, after the maintenance has taken place, the asset managers need to monitor and analyse whether the policy goals made at the strategic level are met. Lastly, asset managers are responsible for evaluating and adjusting the asset management system.

Figure 4 - iAMPro model CROW (adapted and translated from Dutch) [55] [47]

3.3.3 Datasets and Indicators that can be used for infrastructure asset management

According to Mohammadi and Amador Jimenez, an initial step in the process of implementing asset management in an organisation is to set up an asset inventory [5]. How comprehensive an asset inventory is depends on the organisation's asset management policies and experience [5]. A basic asset inventory database should at least consist of a list of assets, their attributes, and their age [5]. Asset managers that collect more detailed data such as time-series data are more mature in their asset management [5]. Data that can be collected may relate to physical attributes (e.g. segment ID, location, direction and number of lanes), deterioration characteristics (e.g. function, traffic intensity, surface material and environmental conditions), and conditions (e.g. age and

International Roughness Index) [5]. Furthermore, information could also be collected on system performance such as accessibility, safety and travel time [5].

The goals of an organisation determine which indicators are used in relation to technical, social and economic aspects to make choices regarding asset management [5]. Indicators can be both qualitative and quantitative.

4 METHODOLOGY

In this chapter, the method used to answer the main question "*What indicators, data and changes are necessary to assess whether the goals of the asset managers of the future are being met, and to support more strategic decision-making?*" is discussed. To answer this main question, the following qualitative research methods are used: interviews, a validation workshop, and desk research [56] [57].

The research is conducted in several steps (see Figure 5). (1) First, information is collected and reviewed regarding the current national, provincial, and local goals related to road asset management. This is done by conducting a semi-systematic literature review and by conducting semi-structured interviews with asset managers of 8 different municipalities, 1 province, and 1 expert in the field of asset management (see Section 4.1). (2) Secondly, a semi-systematic literature review is conducted and semi-structured interviews are held with the same interviewees as in step 1 to create insight into their current working practice and to identify the indicators and data used by asset managers of municipal roads and to get insight into which indicators and data they do not have but need in the future to make strategic decisions in line with their policy (see Section 4.2 and 4.3). (3) The third step is to evaluate the identified indicators and data collection needs of step 2 and to create insight into the barriers to implementing indicators and the collection of data that can help to make better strategic decisions. (4) The final step includes a validation workshop to assess and validate the findings of the interviews and desk research and to create a plan on how the identified indicators and required data collection needed for better strategic decision making can be integrated within the working practices of a municipality (see Section 4.4).

This chapter explains the research methods used to address each sub-question, which together form the answer to the main research question.

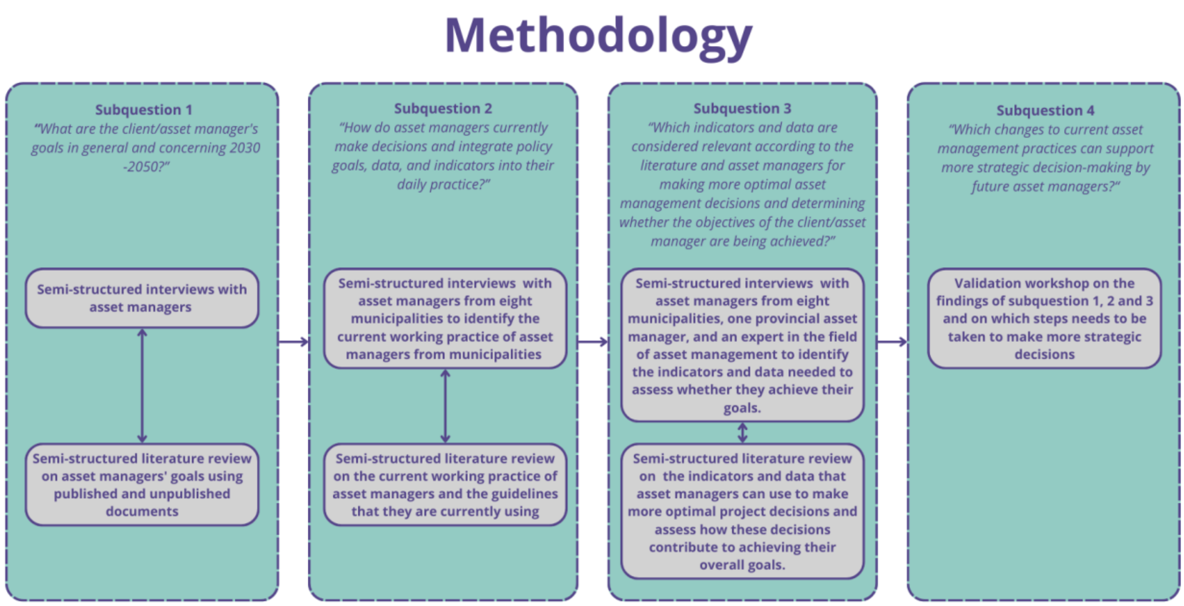


Figure 5 – Methodology

4.1 SUB-QUESTION 1

Sub-question 1 is as follows: *What are the client/asset manager's goals in general and concerning 2030 -2050?.* To answer this question, two qualitative research methods are applied: desk research and interviews. In Section 4.1.1, it is explained how the desk research is conducted. Subsequently, in Section 4.1.2, the methodology for the interviews is discussed.

4.1.1 Desk research

First of all, desk research is conducted [56]. During this process, policy documents from several municipalities regarding the asset management of roads are reviewed to gain a clear understanding of the municipalities' goals regarding asset management. Additionally, policy documents developed at the national and provincial levels, as well as those created by Rijkswaterstaat, are examined to gain a broader perspective on the objectives set by clients concerning road maintenance (see Chapter 3). Not all municipalities published their road asset management plan documents online. If this were the case, the municipalities were asked during the interviews if they had a policy regarding road asset management and if the interviewer could get access to these files.

4.1.2 Interviews

Next, interviews are conducted with asset managers to gain deeper insights into their goals and to validate the findings from the literature review. In these interviews, also questions related to sub-questions 2 and 3 are asked to the interviewees, since all these sub-questions are related to each other. Therefore, the purpose of these interviews is also to understand the current working practices of road agencies and improvements that can be made to reach all the goals of asset managers.

The interviews are conducted in Dutch since this is the native language of the asset managers and the interviewer. These interviews are conducted in a semi-structured manner to create room for open discussions. In semi-structured interviews, a set of questions is prepared in advance, but there is also flexibility to ask follow-up questions for clarification and adjust the questions during the interview [58]. This research method is chosen instead of structured interviews or surveys, since the answers of the interviewees can differ, and follow-up questions can provide more detailed insight into the needs, current working practices and problems described by the asset managers. The duration of the interviews is between 60 and 120 minutes, depending on the answers of the interviewee. The interviews are conducted either face-to-face or remotely via MS Teams, depending on arrangements with the participants. Before conducting the interviews, an interview protocol is developed. This protocol includes the following elements (see Appendix A for the full interview protocol) [58]:

1) A description of the research question
2) A list of individuals involved in the research
3) An introduction explaining the research objectives and how the researcher will use the gathered information
4) The process the interviewer will follow
5) A list of main and follow-up questions. These questions are divided into several categories:
    a. The activities of the interviewee and their definition of asset management
    b. The goals of asset managers
    c. Indicators to measure the goals of asset managers and to base decisions on
    d. Prioritising decisions
    e. Monitoring the conditions of roads and data collection
    f. Literature
    g. The future of asset managers

h. Additional discussion points
6) A note of thanks to the interviewee for their participation

In total, 10 asset managers of 8 municipalities, 1 asset manager of a province and 1 expert who often works with asset managers are interviewed. Table 1 provides an overview of the interviewees. For privacy reasons, the names of the interviewees are not listed in the table. The number of interviews was determined based on the concept of "saturation", meaning that additional interviews were not expected to yield significantly new insights, as responses became increasingly repetitive [59]. While conducting more interviews might have provided some additional perspectives, the marginal benefit of each additional interview was expected to decline. Given the time constraints of this research and the limited added value of further interviews, it was decided to conduct eleven interviews. Snowball sampling is used during the interviews to identify relevant individuals to interview.

Table 1 - List of interviewees

Interview number	Role interviewee within their organisation
1.	Asset manager; mainly responsible for small road maintenance.
2.	Senior advisor city district management; responsible for making a yearly maintenance plan by combining data on roads, the sewerage system and additional requests from other parties.
3.	Advisor roads; responsible for the asset management of roads. He also performs inspections and is responsible for supervising small maintenance on roads. For large maintenance on roads, he has an advisory role.
4.	Policy advisor roads: mainly responsible for the management and maintenance of roads.
5.	Management regisseur: bringing together asset experts to make a program
6.	Department manager of public space; responsible for everything in the public space, and for making a program.
7.	Asset manager of roads; responsible for the maintenance of roads.
8.	Asset manager of roads and civil structures.
9.	Asset manager of roads; responsible for roads, verges, ditches, anti-icing, all street furniture, public lighting, and 3 harbours.
10.	Asset manager of a province in the Netherlands.
11.	Expert in the field of asset management.
12.	Technical management advisor for civil engineering works and infrastructure at a municipality.

All the interviews are recorded with the consent of the interviewees. Following the interviews, each interview recording was transcribed using Microsoft Word. Before conducting the interviews, the interview questions were analysed to identify potential categories or themes into which participants' responses could be classified [57]. After conducting the interviews, the responses were examined to determine how they corresponded to the predefined themes, and an overview was created in Microsoft Excel, mapping each respondent's input to the relevant categories. Additionally, interesting quotes mentioned during the interviews were documented separately for potential use in the analysis and reporting.

4.2 SUB-QUESTION 2

Sub-question 2 is as follows: *How do asset managers currently make decisions and integrate policy goals, data, and indicators into their daily practice?.* To answer this question, two qualitative research methods are applied: desk research and interviews. In Section 4.2.1, it is described how the desk research is conducted. Subsequently, in Section 4.2.2, it is explained how the interviews are conducted.

4.2.1 Desk research

To answer the second sub-question, a review is conducted of the guidelines currently used by asset managers to support their decision-making process, such as the CROW guidelines. The relevant guidelines are identified by asking asset managers during interviews which ones they follow. The aim of this desk research is to gain a deeper understanding of the current working practices of asset managers.

4.2.2 Interviews

Moreover, interviews are conducted with asset managers to map their current working practices so that it can be identified which improvements can be made in their current working practices to enable a more strategic decision-making process. In Section 4.1.2, the procedure for setting up the interviews, conducting the interviews and analysing the interviews is explained. The conducted interview relates to the first three sub-questions, given the interdependence of these questions.

4.3 SUB-QUESTION 3

Sub-question 3 is as follows: *Which indicators and data are considered relevant according to literature and asset managers for making optimal asset management decisions and determining whether the objectives of the client/asset manager are being achieved?.* To answer this question, two qualitative research methods are applied: desk research and interviews. In Section 4.3.1, it is described how the desk research is conducted. Subsequently, in Section 4.3.2, it is explained how the interviews are conducted.

4.3.1 Desk research

To answer the third sub-question, it is important to search for literature on indicators. To find this literature, search engines such as Google Scholar, the online UT library, and Scopus are utilised. The literature review is conducted in a semi-structured manner. Additionally, documents from road authorities and organisations such as CROW are examined to identify indicators that are currently used and considered relevant for learning from projects and measuring whether the goals of asset managers have been achieved. Besides, during interviews with asset managers, the question was asked if they also used particular documents on which they base their indicators. Subsequently, these documents are analysed.

4.3.2 Interviews

Additionally, interviews are conducted with asset managers to examine both the indicators and data they currently use for strategic decision-making and the indicators and data that they anticipate needing in the future. The primary objective of these interviews is to gain a deeper understanding of how asset managers currently perform their tasks and how they envision the future of asset management. Furthermore, these interviews aim to identify which indicators are considered most essential to asset managers. The interviews are conducted as explained in Section 4.1.2. For this sub-question, mainly the interview questions related to the following categories mentioned in the interview protocol are relevant (see Appendix A): (1) Indicators to measure the goals of asset managers and to base decisions on, (2) Prioritising decisions, (3) Monitoring the conditions of roads and data collection and (4) The future of asset managers.

4.4 SUB-QUESTION 4

Sub-question 4 is as follows: *Which changes to current asset management practices can support more strategic decision-making by future asset managers?.* To answer this question, the results of sub-questions 1, 2 and 3 are used, and a validation workshop is conducted (see Section 4.4.1).

4.4.1 Validation workshop

After addressing sub-questions 1, 2 and 3, the necessary data and indicators for enabling more strategic decision-making are identified. Subsequently, it is important to validate these findings and to determine the institutional and practical changes required to implement these indicators effectively, thereby supporting asset managers of the future in making more strategic decisions. To explore these changes, a small-scale validation workshop is organised with a duration of 3 to 4 hours (see Appendix B for the invitation and Appendix C for the workshop PowerPoint slides). A validation workshop is a meeting between evaluators and key stakeholders to review findings [60]. This workshop brings together a diverse group of stakeholders, including asset managers, contractors, municipal project leaders, and an academic expert from the University of Twente, to provide feedback on the relevance of the identified indicators and data, as well as the challenges associated with their implementation.

The workshop participants are challenged to engage in discussions with each other and to provide feedback on the findings of the interviews and the desk research. This process aims to validate the findings of the interviews and the desk research, and to identify which changes are required to facilitate more strategic decision-making by asset managers of the future. A workshop format involving multiple stakeholders was deliberately chosen to ensure a well-balanced perspective on the results. Moreover, this method is expected to generate a greater impact than, for instance, individual validation meetings. By bringing together diverse stakeholders, the workshop can help plant the seed for a future in which the objectives of municipalities are achieved collectively.

5 RESULTS – CURRENT SITUATION

This chapter outlines the current context in which asset managers operate. It begins by describing their tasks, based on insights from both literature and interviews, and identifies the goals that asset managers currently pursue (see Section 5.1). Subsequently, Section 5.2 discusses the decision-making processes asset managers currently use to achieve these goals. Next, Section 5.3 examines the indicators currently used by asset managers, as well as those recommended in the literature. Lastly, Section 5.4 explains the monitoring and data collection techniques which are currently used in relation to these indicators.

5.1 THE ROLE OF CURRENT INFRASTRUCTURE ASSET MANAGERS & THEIR GOALS

In this section, it is explained what the current role of infrastructure asset managers is and what goals they have. The goals and role of asset managers are derived from interviews and literature.

5.1.1 The Role of Infrastructure Asset Managers

The literature presents various definitions of infrastructure asset management. Too (2010) defines it as “a strategic and systematic process of optimising decision-making in resources allocation with the goal of achieving planned alignment of an infrastructure asset with corporate goals throughout its lifecycle” [7]. Additionally, the road policy of the municipality of Enschede defines asset management (translated from Dutch) as "the management and maintenance of public space." [51]. The road policy of Enschede further emphasises that strategic tasks involve balancing policy, performance, risks, and costs [51]. This balance between cost, performance and risk is also mentioned in, for instance, the asset management plan of the municipality of Rotterdam [53]. In the asset management plan for the roads of Rotterdam, asset management is described as follows (translated from Dutch): “Asset management is the next step in professional public space management. The method helps in choosing the right measures and being able to explain them clearly. Asset management ensures that budgets are used where they are needed most. The method widens the scope of technical management and looks at all the social values an ‘asset’ can add to the city. It is about finding the right balance between costs, performance and risks. Management is tackled programmatically and risk-driven in a long-term perspective, also looking at the opportunities for the city.” [53].

However, interviews with asset managers revealed that not all interviewees had a clear definition of asset management and that definitions between asset managers varied. Nevertheless, several key responsibilities were consistently mentioned as part of the role of infrastructure asset managers, including:

- Planning of the maintenance of roads as efficiently as possible;
- Keeping roads safe by reaching a certain quality level;
- Dealing with complaints about roads;
- Predicting needed maintenance;
- Managing roads in a way that brings the most value to society.

Moreover, some of the interviewed municipalities mentioned that they use the iAMPro model for asset management, developed by CROW, as explained in Section 3.3.2.

5.1.2 The goals of asset managers identified based on literature and interviews

One component of the iAMPro model, described in Section 3.3.2, is to define a policy and strategy [55]. In this section, it is explained which goals are described in the policies of several municipalities. However, it must be noted that not all of the interviewed municipalities have a written policy regarding the asset management of roads.

As already mentioned in Section 3.2, it became clear from policy documents that municipalities have several goals they want to achieve. For this study, the policies of multiple municipalities in the Netherlands are considered. The objectives that are mentioned in municipal road policy documents often relate to **safety, health, climate adaptation, image, economy, resilience, biodiversity, accessibility, citizen participation, climate neutrality and circularity** [50] [51] [52] [53]. It was validated during the validation workshop that these goals are important to asset managers. From the validation workshop, it became clear that goals related to **integrality, improving productivity,** and **socially responsible procurement and purchasing** (Maatschappelijk Verantwoord Opdrachtgeven en Inkopen – MVOI) are also important for asset managers to consider in the future. However, these can be seen as sub-goals for the earlier-mentioned goals.

Nevertheless, from interviews with asset managers, it became clear that not all the asset managers considered all these goals from policies in practice. In practice, the focus of many asset managers is mainly on goals related to safety, accessibility, and maintaining roads at a certain standard. Almost all interviewees mentioned that these goals are important to them. However, future asset managers must also integrate sustainability objectives into their decision-making process to reach the sustainability goals set for 2050. This gap between policy and practice found during the interviews is also validated during the validation workshop.

During the interviews, it was mentioned multiple times that the most important goal for asset managers is to keep the roads maintained to a certain quality level, such that the roads remain safe. This is important to asset managers since the municipalities are responsible for damages or injuries because of damaged roads that they own, according to article 6:174 BW [61].

The quality standards that municipalities aim for are often based on the CROW guidelines, which define five quality levels: A+, A, B, C, and D [12]. These quality levels can be described as follows [12]:

- A+: no damage
- A: some damage but warning limits are not yet exceeded
- B: warning limits have been exceeded and major maintenance is needed within 5 years or minor maintenance is required
- C: the guideline has been exceeded and major maintenance is needed within two years
- D: The guideline has been exceeded in more than one class; major maintenance is needed immediately

The quality level that is aimed for is different between municipalities. In some municipalities, the target quality levels for roads depend on their usage and importance within the local infrastructure. The municipality of Enschede, for example, aims to maintain high-quality levels in the inner city (level A), while basic quality levels (level B) apply to the rest of the city. An exception is made for residential streets with element paving, where a lower quality level is acceptable (level C). Pedestrian and cycling paths must be maintained at a basic-plus quality level, ensuring good road conditions for these vulnerable road users [51]. Several other municipalities adopt a policy of maintaining the quality of their entire road network at, for instance, the B or C level. In current practice, maintenance actions are primarily taken in response to road damage.

Current situation:

- Asset managers focus mainly on cost, technical road quality during the roads' use phase and accessibility

Desired situation:

- Asset managers should to a greater extent take de sustainable development goals into account in daily practice if they want to achieve these goals for 2030 and 2050
- Asset managers need a longer-term vision such that cost can be lowered, the average technical quality becomes higher, and sustainability principles are more integrated over the whole life cycle

5.2 DECISION-MAKING PROCESS

To maintain their roads to a certain quality level, asset managers follow a certain decision-making process. During the interviews, it became clear that every municipality has a different method for prioritising the needed maintenance on its roads. Some municipalities mainly prioritise based on the results of the CROW inspections, while others mainly prioritise based on the results of visual inspections that they perform themselves.

A general prioritising pattern that was followed by almost every municipality could be identified after conducting the interview. In Figure 6, this pattern is visualised. Note that the details of this process can differ between the different municipalities. However, almost all municipalities use a reactive process for road maintenance based on the technical status of the road.

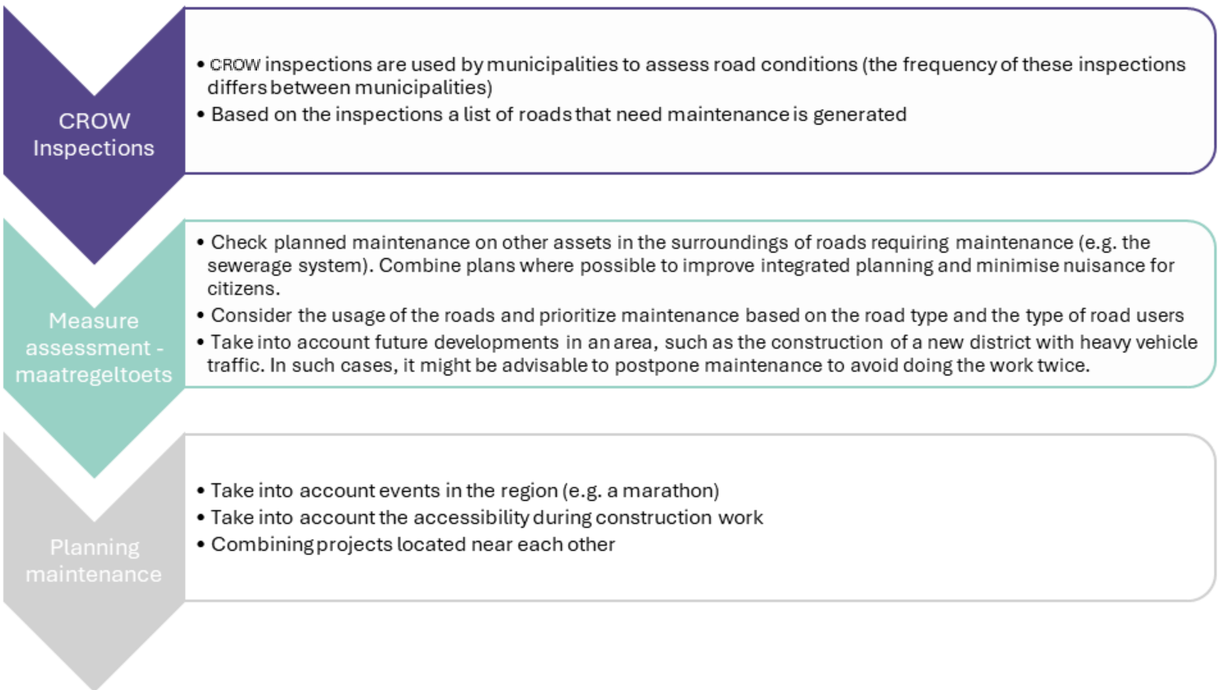


Figure 6 - Prioritising process

As illustrated in Figure 6, the CROW inspections serve as the initial basis for many asset managers to identify roads in need of maintenance. Many of the interviewed municipalities mentioned the necessity of prioritising maintenance activities due to insufficient budgets to address all of the maintenance recommended by the CROW inspection. Furthermore, the advised maintenance recommendations derived from the CROW inspections do not take into account activities in the surrounding area, while these activities are crucial to consider according to asset managers.

Therefore, a measure assessment (maatregeltoets) is done by the asset managers of many municipalities to assess the proposed maintenance by the CROW. This assessment is often done based on personal experience and is also influenced by political interests. There are some aspects that every municipality seems to take into account. For instance, safety has been shown to be one of the most important aspects for prioritising maintenance activities. The level of safety can be connected to the technical quality of the road [62].

During conversations with asset managers, it also became clear that they all consider it essential to combine maintenance on multiple assets whenever possible. For example, if the sewerage system is being maintained in a given year, they prefer to align this with road maintenance to avoid waste of capital and to minimise inconvenience for residents. One municipality even set the goal of limiting road closures for construction to once every ten years. Therefore, asset managers consider the maintenance of other assets in their measure assessment.

Besides, during the measure assessment, asset managers consider future developments in an area, such as the construction of a new district with causes more heavy vehicle traffic. If such a development is going on, it might be advisable to postpone maintenance to avoid doing the work twice.

Moreover, it is often mentioned in the interviews that, for instance, the type of road, location of the road and the type of road user are important to consider during prioritisation. For many municipalities, it seems to be a priority to upkeep the quality of roads with a high traffic intensity. Besides, bicycle lanes and pedestrian lanes around nursing homes seem to have more priority since cyclists and people living in nursing homes are more vulnerable to a hole in the road than, for instance, a car user.

After identifying the maintenance activities for the upcoming year, asset managers must develop a plan. During this planning phase, several practical considerations need to be taken into account. For example, certain roads cannot be closed during events such as sports competitions. Additionally, not all maintenance activities can be executed simultaneously, as the city must remain accessible throughout the process.

During interviews, it became clear that goals such as circularity are often not considered in this decision-making process. This finding was validated in the validation workshop. In the validation workshop, it was added by one of the participants that it is important to consider circularity already in the design phase of a road and that this is currently not always done.

5.3 INDICATORS

This section discusses the indicators that municipalities currently use to assess whether they are meeting their targets and which they can use in their decision-making process. It also examines the indicators that asset managers often lack but are likely to need in the future. First, it explains how indicators are currently formulated (see Section 5.3.1). Then, it discusses the current use of technical and cost indicators (see Section 5.3.2), indicators related to developments (see Section 5.3.3), and indicators concerning product and process quality (see Section 5.3.4).

5.3.1 Current practice in formulating indicators

During interviews with asset managers, it became clear that many asset managers struggled with formulating the indicators they use to make strategic decisions to reach their goals, as mentioned in Sections 3.2 and 5.1.2. According to the iAMPRo model, having measurable indicators is needed to monitor whether the municipality's goals are being met [55].

Interviews revealed that asset managers mainly focus on the maintenance phase of a road's life cycle, relying primarily on technical parameters and costs. While they acknowledge the importance of integrating developments in their maintenance strategy to achieve objectives such as the Sustainable Development Goals, asset managers are still exploring the most effective approach to reaching these targets. At the moment, most asset managers do not have a standard set of indicators to measure to which extent they reach their sustainability goals. Furthermore, their focus appears to be less on the production and construction process of new roads. Instead, asset managers place considerable trust in contractors to deliver high-quality roads, resulting in limited use of data from the construction process.

Several interviewees also mentioned that their decision-making was largely based on personal experience, and they found it challenging to translate these experiences into measurable indicators. In one municipality, the recent retirement of the road asset manager resulted in a loss of valuable knowledge for decision-making, showing the dependency on the experience of asset managers. Additionally, some municipalities had not clearly defined their goals, further complicating the formulation of clear indicators.

Besides, the interviews revealed differing perspectives on the use of current indicators. Some asset managers rely mainly on the quality indicators outlined in the CROW guidelines, such as transverse unevenness, cracking, ravelling, and edge damage. These asset managers base their strategic decisions on the number of observed damage types during the CROW inspections and the severity of the identified damages. Other asset managers prefer more visual and contextual indicators, arguing that CROW inspections quantify the damages to roads only in numbers, which, in their view, does not tell the whole story. They emphasise the importance of considering the broader context in which a road is situated.

Moreover, the interviews revealed that for certain objectives set in policy documents, asset managers were unable to clearly define specific indicators to measure whether these goals were being achieved. For example, it became apparent that asset managers struggled to formulate indicators related to objectives such as climate adaptation and biodiversity, despite these topics being frequently mentioned in policy documents. It was mentioned during one of the interviews that during maintenance, especially small maintenance, often the same product is used as before, which makes it difficult to improve the climate adaptability of a road during maintenance. It seems from the interviews that asset managers primarily focus on indicators related to the technical quality of roads during their operational phase. Some of the asset managers found these indicators sufficient for doing their job, while others were missing indicators related to, for instance, the remaining life span of a road, integrality and real-time indicators.

Furthermore, the location of the municipality also has an impact on the indicators that asset managers focus on. In the west of the Netherlands, for example, there are problems related to soil settlement, which is important to include in the indicators. In the Veluwe area, for instance, they do not have this kind of problem and an indicator related to settlement is not needed.

In the following sections, it is described for multiple strategic goals which indicators can be used according to the interviewees and the literature to measure the extent to which the goals are reached. It is chosen to focus on the goals related to safety, appearance, durability, comfort, climate neutrality, circularity, climate adaptation and costs since asset managers of roads have the most influence on these goals.

Current situation:

- Indicators are mainly focused on the CROW guidelines (publications 146 & 147)
- Indicators are based on experience
- Lack of indicators to measure if sustainability goals are achieved
- The importance of indicators sometimes depends on the location of a municipality

Desired situation:

- More indicators to measure goals related to sustainability

5.3.2 Road Management Indicators

Current road management goals primarily focus on maintaining road quality to a defined standard in the most efficient manner, ensuring that roads remain safe, accessible, comfortable, and visually appealing. Therefore, technical quality indicators and indicators related to costs are discussed in this section.

5.3.2.1 Technical Quality Indicators

Firstly, technical indicators are discussed in this section that are currently used and can serve as an indication of whether the objectives of asset managers regarding safety, aesthetics, comfort, and durability are being achieved [12]. Some of these indicators can be determined visually, while others require measurements.

5.3.2.1.1 The need for technical indicators

As mentioned in Section 3.3.2, municipalities are responsible for ensuring that their roads are in good condition according to Article 16 of the Wegenwet. If damages or injuries occur because of roads that are not in good condition, then the owner of that road is responsible according to the law (article 6:174 BW). Therefore, municipalities aim to maintain the technical quality of their roads to a certain standard. During the interview, it was also often mentioned that the technical quality of the roads is one of the most important aspects for asset managers to focus on. According to the CROW guidelines, these technical indicators are also related to the goals of the municipalities such as safety, appearance, durability and comfort [12]. Hence, it is important for municipalities to maintain the quality of their roads to a certain standard.

5.3.2.1.2 Definition of technical quality

During the use phase of asphalt roads, the roads deteriorate. To evaluate the pavement's technical conditions during the use phase, it is crucial to assess the following technical parameters: transverse evenness, longitudinal evenness, surface texture, friction, cracking, other surface defects and bearing capacity [29] [30]. These technical parameters give insight into the performance of asphalt roads.

5.3.2.1.3 Indicators to measure technical quality

Two types of indicators can be used to measure the performance of roads according to the literature: functional and structural indicators [29]. The functional indicators relate to the ride quality and safety of the asphalt pavement, and the structural indicators refer to the ability of the pavement to withstand traffic load [29]. According to Marcelino et al. (2017), both types of indicators are important to assess the performance of the asphalt road, and in the ideal situation, there would be comprehensive performance indicators that could express all this information [29]. However, Marcelino et al. (2017) argue that collecting all data needed for these indicators is expensive, so a balance needs to be made in what data is essential to collect and the costs [29].

Currently, asset managers assess road quality primarily through damage notifications and CROW indicators. To assess the quality of their roads, all interviewed municipalities conduct inspections in accordance with the CROW guidelines [48] [12]. The frequency of these inspections varies between municipalities, with most performing them once a year or once every two years. These inspections are carried out visually, focusing on damages such as ravelling, transverse unevenness, general unevenness, cracking, setting, and edge damage [48]. Additionally, measurements can be done to, for instance, determine the longitudinal unevenness and rutting [12]. The literature suggests that additional indicators can also be used to evaluate the technical condition of roads. The following sections provide a detailed discussion of these indicators

5.3.2.1.3.1 Damage notifications – Standard indicator used by asset managers of municipalities

First of all, the amount of damage reported by citizens can indicate the technical quality of a road, according to the interviewees. In many of the interviews with asset managers, it emerged that the number of damage reports at a particular location can give insight into damage to the road. Multiple asset managers are using damage notifications as indicators for road quality.

5.3.2.1.3.2 The indicators of the CROW – Main indicator used by asset managers of municipalities

All of the interviewed municipalities use the CROW method to inspect their roads and to determine their maintenance strategy. During these CROW inspections, the severity and scale of the damage on roads are determined visually [48]. The damages that are taken into account in the visual CROW inspections are ravelling, transverse unevenness, general unevenness, cracking, settlement of the ground, and edge damage [48] [12].

During the interviews, it was mentioned that these indicators give a solid insight into the quality of the roads. However, some interviewees suggested that the results would be more useful if the damage locations were recorded during inspections and mapped. Additionally, one interviewee mentioned that there is subjectivity involved in CROW inspections, as assessments depend on the inspectors' judgments, which is seen as undesirable. As a result, this interviewee argued that efforts should be made to minimise subjectivity in the inspection process. These interview findings were validated during the validation workshop.

Many of the municipalities do not perform measurements for longitudinal unevenness and rutting, which can be done according to the CROW. However, these measurements are carried out for provincial roads. An interview with the province revealed that these measurements have added value because some aspects are not easily observed visually. At the province, the international roughness index (IRI) and rut depth are measured. During the interview with the province, it emerged that these measurements have added value for them. Based on these measurements, they can compare how these values develop over the years. Furthermore, these measurements can also be done when weather conditions are not optimal and measurements are objective. However, unreliable data does need to be filtered out of the results. This includes, for example, data collected at a roundabout that gives a biased picture of the rest of the road.

The CROW guidelines define acceptable damage levels for different road types, which can help determine when maintenance should be carried out [12]. If the damage exceeds the guideline limit, maintenance should take place within one to two years [12]. When the damage surpasses the warning limit but remains below the guideline limit, maintenance is required within three to five years [12]. If the damage has not yet reached the warning limit, maintenance can be scheduled for five or more years into the future [12]. Note that these actions mentioned in the CROW guideline are all based on reactive maintenance.

5.3.2.1.3.3 Transverse evenness – Indicator from literature, hardly used by asset managers of municipalities

To measure the transverse evenness, the rut depth can be considered [63] [64]. Also, other indicators can be used to express the transverse evenness according to a literature study done by Fares et al. (2024), such as the rut width, rut length, rut volume, and the rut cross-sectional area [63]. According to a literature review performed by Fares et al. (2024), the most commonly found rutting index in the literature is the rutting depth [63]. This rutting depth can be measured with rut bars with as advantage that the data collection process is automated [63]. The disadvantage of rut bars is that they can have a low accuracy and a high variability [63]. Faras et al. (2024) also emphasise that rutting measurements can be expensive, which can be financially unfeasible for municipalities and that therefore more research needs to be done on low-cost methods, such as depth cameras, for rutting measurements [63]. At the moment, transverse evenness is not standard measured by asset managers. It is only measured in specific situations. Asset managers mainly assess transverse evenness visually according to the CROW guideline. However, measurements can offer more detailed data and greater insight into the progression of rutting over time. Measurements are not always done at the moment by asset managers of municipalities, due to aspects such as the costs of these measurements.

5.3.2.1.3.4 Longitudinal evenness; the International Roughness Index (IRI) – Indicator from literature, hardly used by asset managers of municipalities

One of the most commonly mentioned indicators for road quality in the literature is the International Roughness Index (IRI). However, as mentioned in Section 5.3.2.1.3.2, the IRI is often not considered by asset managers of municipalities. The IRI represents the roughness of a road in meters per kilometre [65]. According to Dela Cruz et al. (2021), the IRI represents the virtual movement of the sprung and non-sprung masses, normalized by the profile length [65]. The lower the IRI, the smoother the road is. The IRI values can indicate the quality of the road [64]. For instance, Yu et al. (2006), proposed ride quality thresholds based on the IRI at different speeds [66].

The IRI in combination with the mean profile depth of a road have an impact on the rolling resistance and hence the fuel consumption of the road users [67]. The amount of fuel consumption that can be reduced by improving the IRI and mean profile depth is at the moment not considered by asset managers. During the interviews, it became clear that most asset managers never thought about the environmental results of a poorly maintained road. During the validation workshop, the participants also mentioned that they wonder if it is needed to consider this extra fuel consumption.

Measuring equipment is required to capture the road profile, which is essential for calculating the IRI. Multiple measurement tools are available to measure the road profile, such as laser sensors at both wheel paths [65]. Subsequently, the measured road profile needs to be processed by a mathematical algorithm to get the actual IRI [65]. Research has explored the use of alternative methods, such as mobile phones, to measure the IRI [65]. However, these approaches currently face certain limitations [65].

During an interview with an expert in the field of asset management, it appears that she understands why municipalities often do not use the IRI. On municipal roads where the speeds are low, it might not be beneficial to measure the IRI, since the cost of doing the measurements might not outweigh the benefits that the measurements bring.

5.3.2.1.3.5 Macro texture - Indicator from literature, hardly used by asset managers of municipalities

The macro texture influences the friction of a road, which affects road safety [68]. The macro texture can be measured with, for instance, the mean texture depth or the mean profile depth [69] [64]. However, in the interviews, it became clear that the macro texture was often not measured by municipalities. The mean profile depth can be measured effectively and quickly with the help of a laser profiler [69]. Using the mean texture depth indicator is more time-consuming according to Plati et al. (2017) and can be derived while using the sand patch method [69]. It can be beneficial for asset managers to consider this indicator since it gives insight into goals related to safety.

5.3.2.1.3.6 Pavement Condition Index (PCI) - Indicator from literature, not used by asset managers of municipalities

The pavement condition index (PCI) is developed for the US Air Force in the late 1980s by the US Army Corps of Engineers [70]. The PCI is an index with a scale from 0 to 100 and is based on multiple distress types. These distress types and the severities of these (i.e. high, medium, low) are based on the results of a visual condition survey [70]. In the paper of Shiyab (2007), multiple methods are shown to determine the PCI [70]. A limitation of this PCI indicator is that it is a single-number index which does not always give a correct representation of the pavement condition [70]. During the interviews, it became clear that the PCI is not considered by asset managers of municipalities in the Netherlands to determine the pavement conditions. For them, this indicator is unlikely to offer additional valuable insights, as it is similar to the CROW indicators and does not provide more detailed information on specific road damages.

5.3.2.1.3.7 Pavement Serviceability Index (PSI) - Indicator from literature, not used by asset managers of municipalities

The pavement serviceability index provides insight into how well road users are served [71]. Since it is impractical to gather the opinions of multiple roadway users about a certain road, objective parameters related to the user experience are often used to determine the pavement serviceability index [71]. In the literature, multiple parameters are used to estimate the PSI. Aleadelat et al. (2017), propose a PSI that is dependent on the pavement condition index, the international roughness index and the pavement rutting [71]. While Hall et al. (1999), propose an equation to calculate the pavement serviceability index that is only dependent on the international roughness index [72]. During the interviews with asset managers of municipalities in the Netherlands, it became clear that they do not use this indicator. For them, this indicator would likely offer limited added value, as existing indicators such as the CROW indicators already provide an indirect measure of how well road users are served.

5.3.2.1.3.8 Falling weight deflectometer – Indicator from literature, hardly used by asset managers of municipalities

In interviews with multiple asset managers of municipalities in the Netherlands, it became clear that falling weight deflectometer tests are useful for determining the remaining lifespan of an asphalt road. This measurement for the bearing capacity of the road is quite expensive, according to the interviewees, and therefore, they seldom use it. However, if they had more information on the bearing strength of roads, this could help them improve their maintenance strategy since they would have more insight into their roads' remaining lifespan. Therefore, the interviewees mentioned that it would be beneficial to do more falling weight deflection measurements.

5.3.2.1.3.9 Friction – Indicator from literature, hardly used by asset managers of municipalities

According to the literature, pavement friction is one of the most essential properties of a road [73]. It is an important parameter since there is a strong correlation between road friction and accident risk [73]. However, in many of the interviewed municipalities, the friction of roads is not measured. According to the interviewed expert, skid resistance of a road is an important indicator that might also be beneficial to consider by municipalities since it affects safety. The friction of a road can be measured with different types of devices [73]. A study concluded that various countries use different measurement methods and that there is a need to harmonise road friction measurements [73]. The friction can be represented in a friction index [73]. The lower the friction coefficient, the longer the stopping distance of a car is [73].

Indicators that are currently used:

- Visual CROW indicators based on severity and scale (ravelling, transverse unevenness, general unevenness, cracking, setting, and edge damage)
- Damage notifications of citizens

List of possible additional technical indicators according to the literature:

- Rut depth
- International Roughness Index
- Mean Profile Depth
- Pavement Serviceability Index
- Pavement Condition Index
- Falling weight deflectometer test
- Friction Index

Need and obstacles to apply more indicators:

- **Need:** there is a need for more objective and detailed indicators for the technical quality
- **Obstacle:** measurements are often expensive

5.3.2.2 Cost indicators

In the interviews, asset managers indicated that they aim to maintain their assets to a certain quality level at the lowest possible cost. Additionally, they strive to maximise societal value. This requires asset managers to continuously balance costs against the societal benefits that can be achieved. Therefore, an indicator of the costs incurred by infrastructure managers is needed.

5.3.2.2.1 The need for a cost indicator

Both the interviews and policy documents indicate that cost plays a significant role in asset managers' decision-making processes. Due to limited budgets, asset managers are sometimes unable to carry out all the necessary maintenance, therefore, they need to work as cost-efficiently as possible. The interviews also showed that avoiding capital destruction is a key priority for asset managers. Asset managers prefer not to intervene too late or too early to avoid capital destruction. Additionally, they aim to avoid situations where a road is newly renovated, only to be damaged a few years later by developments in the area, such as heavy construction traffic.

5.3.2.2.2 Definition of costs

In this context, cost is defined as what you have to pay for something in euros.

5.3.2.2.3 Indicators to measure costs

During the interviews, it became apparent that multiple indicators to measure cost can be considered. In practice, mainly investment costs seem to be considered by asset managers, while in the long term, it might be useful to focus on the complete life cycle costs. In literature, it is mentioned that to gain maximum value for money, the commonly used construction cost minimisation approach should be substituted for life cycle cost optimisation [74]. In this section, all cost indicators found in the literature and during the interviews are elaborated on.

5.3.2.2.3.1 Destruction of capital – Currently used by some asset managers of municipalities

During the interviews, it appeared that asset managers want to avoid capital destruction. To avoid this, it is important to consider developments in the surrounding area of a road in need of maintenance. Sometimes, data is still missing on these developments in the surrounding area. If a new residential area is developed, then it might be beneficial to postpone maintenance. Besides, capital destruction can be avoided by performing maintenance on time. The question is how capital destruction can be captured in an indicator. During the interviews, it became clear that the extent to which maintenance is performed earlier or later than necessary can indicate capital destruction. According to the CROW guidelines, capital destruction can be calculated by comparing the costs of postponed maintenance and timely maintenance [62]. An additional indicator of how much capital destruction has been avoided is the number of projects that have actively monitored developments in their environment and adjusted their maintenance strategies accordingly.

5.3.2.2.3.2 Maintenance arrears – Currently used by some asset managers of municipalities

Moreover, several interviewees expressed a desire to gain insight into their maintenance arrears and the estimated financial resources required to eliminate these arrears. In some of the interviewed municipalities, this value is already calculated.

5.3.2.2.3.3 Costs per square meter of road – Currently used by some asset managers of municipalities

The interviews also revealed that cost efficiency could be indicated by the annual maintenance cost per square metre of area. For some municipalities, this serves as a performance indicator to assess how efficiently they carry out maintenance. Besides, according to one of the interviewees, it is important to create insight into the cost, therefore, it might be beneficial to visualise for each type of activity, how much it costs for every square meter of road.

5.3.2.2.3.4 Lifecycle costs – Indicator from literature, hardly used by asset managers of municipalities

It has also emerged during the interviews that municipalities want to extend the lifespan of roads as much as possible. To determine the benefits of these life-extending measures, it is important to consider the life cycle costs. The life cycle costs can be reflected in different types of economic indicators such as the Simple Payback Period Analysis, Cost-Benefit Analysis, Net Present Value, and the Equivalent Uniform Annual Cost [75]. Which economic indicator is most beneficial to use depends on the situation. The advantage of the Equivalent Uniform Annual Cost indicator is that it allows alternatives with different analysis periods to be compared [75]. During the interviews, it appeared that these lifecycle costs are not calculated yet by asset managers.

5.3.2.2.3.5 Social and environmental benefits expressed in a monetary value – Indicator from literature, not used by asset managers of municipalities

Besides, it can be useful to express the social and environmental value of a project in a monetary value. The social and environmental return of an investment can be calculated by dividing the adjusted social and environmental value created by the investment costs [76]. This method could give municipalities insights into the social and environmental benefits that their investment brings. However, this method seems to be hardly used in the Netherlands.

The challenge is to quantify the added social and environmental value in a monetary value. In the literature, almost nothing can be found on how to express these aspects in euros for the Netherlands. According to literature, research has been done on the social return on investment of an urban regeneration project in which eight key elements are considered: (1) property values; (2) flood alleviation; (3) tourism, (4) biodiversity, (5) climate change, (6) health and wellbeing, (7) crime, and (8) employment and productivity [77]. In this study, it also became apparent that it is, for instance, difficult to define the impact on biodiversity in monetary terms [77].

Indicators that are currently used:

- Yearly costs to perform the maintenance strategy
- Destruction of capital
- Maintenance arrears in euros
- Allocation of budgets
- Costs per square meter of road

List of possible additional cost indicators according to the literature:

- Lifecycle costs – Equivalent Uniform Annual Cost indicator
- Social and environmental benefits expressed in a monetary value compared to the size of the investment

Need and obstacles to apply more indicators:

- **Need:** a cost indicator is needed that considers the whole life cycle of a road, so that more strategic decisions can be made in the long term. Besides, data about the maintenance planning of other infrastructure assets and other developments in the surrounding area are needed to avoid capital destruction.
- **Obstacles:**
    - Knowledge is needed within an organisation to calculate the life cycle costs
    - Life cycle costs are based on predictions and these predictions should be accurate
    - Data on the long-term maintenance planning of other assets is needed
    - Data on developments in the surrounding areas of the roads are needed

5.3.3 Developments

This section discusses indicators related to the Sustainable Development Goals. To assess the impact of new production, construction, maintenance, and end-of-life strategies, it is essential to have indicators that measure their effects on climate neutrality, circularity, and climate adaptation. However, most asset managers are not currently focused on these goals. When they do consider them, the indicators used often fail to clearly and transparently reflect the extent to which the goals are being achieved. Therefore, there is a need to improve the indicators used to measure climate neutrality, circularity, and climate adaptation.

5.3.3.1 Climate Neutrality Indicators

Policy documents from various municipalities state that they aim to reduce the amount of emitted CO_2 and other greenhouse gases. However, many interviews revealed that most of the interviewed municipalities did not yet have indicators to measure climate neutrality or that they do not use them. This section explains which indicators asset managers can use to measure climate neutrality according to the literature.

5.3.3.1.1 The need for climate neutrality indicators

The climate is changing rapidly, leading to higher temperatures, more extreme rainfall, prolonged droughts, and rising sea levels [15]. In the Netherlands, the average temperature has increased by 1.8°C since 1900 [15]. Additionally, the annual rainfall increased by 27% between 1910 and 2015 [15], while the intensity of heavy rainfalls, causing water-related issues, has increased by 20% [15]. To minimise the problems caused by climate change, it is important to become climate-neutral by reducing greenhouse gas emissions. This is called "climate mitigation" [15].

5.3.3.1.2 Definition of climate neutrality

Climate neutrality means that your activities are not contributing to global warming [78]. This means that if an organisation emits greenhouse gases, it also has to remove the greenhouse gases that it emits from the air [78]. According to Vendrik et al. (2023), a climate-neutral municipality can be described as (translated from Dutch): "A climate-neutral municipality is a municipality that causes no net greenhouse gas emissions within its own territory." [79]. The following greenhouse gases affect climate change: carbon dioxide (CO_2), methane (CH_4), laughing gas (N_2O), hydrofluorocarbons (HFK), sulphur hexafluoride (SF_6) and perfluorocarbons (PFKs) [79].

5.3.3.1.3 Indicators of climate neutrality

The interviews revealed that becoming climate and CO2-neutral is not a top priority for every asset manager. Currently, some municipalities are trying to reduce their greenhouse gas emissions by adopting electrified equipment. Others are opting for more environmentally friendly asphalt mixes, produced at lower temperatures with biobased binders and recycled materials. However, the interviews also showed that asset managers lack clear indicators to measure the environmental impact of their maintenance strategies.

5.3.3.1.3.1 Production phase

First of all, indicators related to the production process of pavement are relevant to consider for becoming climate-neutral. Since the production phase of asphalt at the plant has a significant impact on emissions during the life cycle of roads, accounting for 26% of total emissions [34]. Additionally, the materials used in asphalt production, particularly aggregates and bitumen, contribute heavily to greenhouse gas emissions. In fact, the extraction of raw materials needed for asphalt has the largest share of emissions, making up 40% of the total greenhouse gas output [34].

Therefore, in the production phase of asphalt, it is important to minimize greenhouse emissions and the usage of primary materials to reach the goals of municipalities to become climate-neutral and circular while keeping the lifespan of the asphalt as long as possible [34] [40] [10] [37] [35]. In literature, it is proposed to use the energy consumption (in the production of asphalt) per ton of asphalt as an indicator to measure the impact of the production process on the environment [80]. When this is done, it might also be beneficial to consider how much of the energy is generated in a sustainable manner. Energy consumption does not give a direct indication of how much greenhouse gas emissions are reduced.

Since the goal of municipalities is to reduce the greenhouse gas emissions during the life cycle of their roads, it is important to consider the greenhouse gas emissions during the various lifecycle stages of the roads. In the interviews, it was often mentioned that the managers found it difficult to determine how to calculate the greenhouse gas emissions during the lifecycle of the road. To calculate the greenhouse emissions during, for instance, the production phase, the Product Category Rules for asphalt can be used [81]. These Product Category Rules are made such that all parties calculate the environmental impact in the same manner [81]. Based on the calculated CO_2 emissions with the Product Category Rules, the amount of CO_2 reduction or gas consumption compared to traditional methods can be compared.

Moreover, the Environmental Cost Indicator (MKI) is frequently used in project procurement to indicate the environmental impact of a product over its entire lifespan. The MKI consolidates various environmental impact scores into a single monetary value through weighting [82]. This method is often used, as comparing one monetary value is easier than assessing multiple separate environmental impact categories [83]. However, the conversations conducted in this research revealed that not everyone views the MKI as a suitable tool for expressing the environmental impact. Some participants argued that reductions in CO_2 emissions, for example, are much easier to comprehend than a reduction in MKI. Furthermore, the reduction in MKI does not say everything about, for instance, the goal of becoming CO2 neutral, as several types of environmental impacts are added together in one monetary number.

Furthermore, a method not mentioned by asset managers during the interviews, but discussed in the literature for evaluating the impact on climate change, involves aggregating all emissions that affect climate change into a single number, expressed in CO2-equivalents, which serves as an indicator of climate neutrality [79]. The benefit of this indicator is that it gives a direct insight into which extent the greenhouse gases that impact global warming are reduced.

5.3.3.1.3.2 Transportation phase

The transportation of asphalt also has a substantial impact on greenhouse gas emissions (6% of the total emissions during the life cycle [84]). Therefore, it can be useful to have an indicator related to the emissions during the transportation phase.

Again, the Product Category Rules can be used to calculate the greenhouse gas emissions during the transportation phase [81]. Besides, indicators can be used such as the transport movements of asphalt per tonne of production [80]. Furthermore, for some projects, it is currently expressed how many transport movements are saved compared to traditional methods. It must be noted that this indicator does not give a direct insight into climate neutrality because this is also dependent on, for instance, the type of truck. Therefore, this indicator is not suitable for measuring climate neutrality.

5.3.3.1.3.3 Construction phase

During the interviews, it also became clear that some municipalities want to electrify their equipment to reduce greenhouse gas emissions during the construction phase. However, one interviewee also mentioned that this is not practical in the countryside areas because there are hardly any charging points. These practical issues related to the electrification of equipment were also confirmed during the validation workshop.

To determine the emissions at the construction phase, again, the Product Category Rules can be used [81]. Additionally, the interviews revealed that the percentage of electric equipment used on-site can serve as an indicator of greenhouse gas emission reductions during the construction phase. It should then also be included how power is generated for these electric vehicles. In one of the interviews, for example, it came up that a project was once done where electric vehicles were used, but to charge the equipment at the construction site, aggregators were used that generated electricity from fossil fuel. In such cases, using electric vehicles is not more environmentally friendly than using vehicles powered by fossil fuels. Therefore, the percentage of electrified equipment is not a direct indicator of climate neutrality, but rather one possible means of contributing to it.

5.3.3.1.3.4 Use phase

During the use phase, the Product Category Rules can also be used to calculate greenhouse gas emissions [81]. However, the Product Category Rules do not take into account the emissions from cars during the use phase, while the technical quality of roads has an impact on the rolling resistance and hence the fuel consumption of the road users [67]. The amount of fuel consumption can be reduced by improving the IRI and MPD. This aspect is at the moment not considered by asset managers. During the interviews, it became clear that most asset managers never thought about the environmental impacts during the use phase of the road.

5.3.3.1.3.5 End-of-life

The Product Category Rules can also be used during the demolition phase of the roads to calculate greenhouse gas emissions [81].

Indicators that are currently used in some projects, but not as standard by asset managers:

- ↗ Energy consumption (in the production of asphalt) per ton of asphalt
- ↗ Number of reduced transport movements
- ↗ Number of transport movements per ton of asphalt
- ↗ Emission calculated for different life cycle phases with the Product Category Rules
- ↗ Environmental Cost Indicator (MKI) calculated with the Product Category Rules

List of possible additional climate neutrality indicators according to the literature:

- ↗ Extra fuel consumption due to higher rolling resistance, which is dependent on the IRI and MPD
- ↗ Total of all greenhouse gases expressed in CO_2 equivalent

Need and obstacles to apply more indicators:

- ↗ **Need:** Indicators are needed that can indicate all emissions that impact climate change (CO_2, CH_4, N_2O, SF_6, NF_3, HFK, PFK's [79]). These indicators should include all emissions during the life cycle. Furthermore, these indicators need to be easy to interpret.
- ↗ **Obstacles:**
  - A more accurate method is needed to estimate the total greenhouse gas emissions over the whole life cycle of the road
  - A long-term perspective is needed, which most asset managers currently do not have. In this perspective, different long-term strategies need to be balanced against each other.

5.3.3.2 Circularity indicators

This section elaborates on indicators that asset managers can use to support decision-making regarding circularity. Interviews with asset managers revealed that circularity is already considered in their decision-making processes. However, in most cases, no explicit indicators are used to measure circularity. Besides, asset managers mainly focus on the circularity principle of "Recycle", while there is a need to also consider circularity principles such as "Reduce", "Reuse" and "Refuse". There seems to be no uniform definition of circularity that is used by all asset managers. This section outlines which indicators can be used to measure circularity according to the literature and the interviewees.

5.3.3.2.1 The need for circularity indicators

As mentioned in Section 3.2, the goal of the Dutch government is to have a fully circular economy by 2050, a goal that is also reflected in regional and local policies [10] [9]. However, in policy documents, it is not clearly stated how circularity can be measured. During interviews, it became clear that the most often used indicator for circularity was the recycled amount of materials in asphalt and to what extent the asphalt can be reused at the end of its life cycle. However, there are more aspects that need to be considered to become fully circular, such as reducing the amount of materials used. Therefore, more indicators are needed to make more strategic decisions about circularity.

5.3.3.2.2 Definition of circularity

The concept of a circular economy is defined in various ways [44]. A widely cited definition comes from the MacArthur Foundation, which describes it as "an industrial economy that is restorative or regenerative by intention and design" [44] [85]. Furthermore, according to the MacArthur Foundation, there are 4 principles to create circular value within a project; the power of the inner circle, the power of circling longer, the power of cascaded use and inbound material/product substitution, and the power of pure, non-toxic or at least easier-to-separate inputs and design [85].

Furthermore, the principles of the 3Rs, 4Rs or 9Rs are commonly used to represent the level of circularity [86]. The first R, refuse, indicates the most circular practice, while the last R, recover energy, represents the least circular approach. The 9Rs are: (1) Refuse, (2) Reduce, (3) Reuse, (4) Repair, (5) Refurbish, (6) Remanufacture, (7) Repurpose, (8) Recycle, and (9) Recover energy [87]. The R-principle serves as a guideline for assessing whether a circular strategy is being implemented [88], but it is not a suitable method for measuring the circular impact of a project [88].

5.3.3.2.3 Indicators to measure circularity

Although almost no circularity indicators are currently implemented in the Netherlands, several indicators have been developed in the literature to measure circularity [89]. These include the Material Circularity Indicator (MCI), the Circular Economy Index (CEI), indicators from platform CB'23, the Environmental Sustainability and Circularity Indicator (ESCi), the Circular Economy Indicator Prototype (CEIP), the Milieu Kosten Indicator (MKI), and the Material Reutilization Score (MRS) [90] [91] [92]. However, almost none of these indicators are used by Dutch asset managers. Dutch asset managers focus mainly on indicators such as the percentage of recycled asphalt, the MKI and the share of biobased binders if they already have a focus on circularity.

5.3.3.2.3.1 Percentage recycled asphalt – Currently used by asset managers of municipalities

An indicator often used to measure circularity is the amount of recycled asphalt. The amount of asphalt recycled is often expressed as a percentage of materials recycled. This indicator does not reflect all aspects of circularity; (1) Refuse, (2) Reduce, (3) Reuse, (4) Repair, (5) Refurbish, (6) Remanufacture, (7) Repurpose, (8) Recycle, and (9) Recover energy [87]. It only reflects the aspect of recycling, which is not the highest level of circularity that can be reached.

5.3.3.2.3.2 Environmental Cost Indicator (MKI) – Currently used by asset managers of municipalities

The Milieu Kosten Indicator (MKI) is currently often used to provide an indication of circularity in projects [93]. In the MKI, several environmental impact scores are converted into a single monetary value through weighting [82]. The MKI value is derived from the shadow pricing methodology [82]. The lower the MKI, the lower the cost of preventive measures needed to avoid environmental impact [82]. In the interviewed province, the MKI that is promised before the project is compared to the actual achieved MKI. This comparison shows that in some projects the actual MKI is much higher than initially promised and that in some projects the MKI is lower than promised. However, the MKI is not a direct measure of circularity because it does not give insight into the material usage. Therefore, other indicators are needed to give a better insight into circularity.

5.3.3.2.3.3 Share of biobased binders – Currently used by asset managers of municipalities

Furthermore, there is an increasing focus on asphalt produced with biobased binders that ensure that the asphalt becomes more circular, an example of this is “Grasfalt”, where 50% of the binder is bitumen and 50% is lignin derived from the crop Miscanthus Giganteus [18]. An indicator of circularity in this case is the percentage of bio-based binders. This indicator gives an indication of the reduction of non-renewable primary resources.

5.3.3.2.3.4 Platform CB’23 indicators - Not often used by asset managers of municipalities at the moment

The CB'23 platform has developed a set of indicators to measure the circularity of construction projects [88] [91]. These indicators focus on material stocks, the environment, and value retention [88] [91]. No method has yet been established by the platform CB’23 to combine the scores of these individual indicators into a total score [88] [91]. In Table 2, a list of all the CB'23 indicators is shown. The first three indicators in this list are based on the weights of materials. With these indicators, the material usage between different maintenance strategies can be compared. The interviews revealed that these indicators are currently rarely used by asset managers in practice.

The CB’23 indicators provide insight into the input and output of materials, distinguishing between renewable and non-renewable resources, and assessing their potential for reuse and recycling in the next lifecycle. However, it is important to note that these indicators are based on weight, which may create a misleading impression, as lightweight, non-renewable materials could be underrepresented. Furthermore, the CB’23 indicators do not explicitly measure the extent to which material usage is reduced.

Besides, the CB’23 primarily offer insights into the reuse and recycling potential of materials at the end of their lifecycle, as well as their functional and technical quality at that stage. Therefore, it might be beneficial to use the CB’23 indicators in the future in combination with indicators that, for instance, indicate what the material reduction is compared to “traditional” methods. However, this requires a definition of the traditional working method and the material usage in this method.

Table 2 - Indicators platform CB'23 [91]

Indicator	**Sub-indicators**		
1. Amount of input materials	1.1. Amount of secondary materials	1.1.1. Amount of secondary material from reuse	
		1.1.2. Amount of secondary material from recycling	
	1.2. Amount of primary materials	1.2.1. Amount of renewable primary materials	1.2.1a Amount of sustainably produced renewable primary materials
			1.2.1b Amount of non-sustainably produced renewable primary materials
		1.2.2. Amount of non-renewable primary materials	
	1.3. Physical scarcity	1.3.1. Amount of physically non-scarce material	
		1.3.2. Amount of physically scarce material	

Indicator	Sub-indicators	
	1.4. Socio-economic scarce materials	1.4.1. Amount of socio-economically non-scarce resources
		1.4.2. Amount of socio-economically scarce resources
2. Available material for the next cycle	2.1. Amount of material for reuse	
	2.2. Amount of material for recycling	
3. Lost material for the next cycle	3.1. Amount of material for energy recovery	
	3.2. Amount of material for landfill	
4. Environmental protection indicators (MKI/MPG)	4.1. Climate change – total	
	4.2. Climate change – fossil	
	4.3. Climate change – biogenic	
	4.4. Climate change – land use and land-use change	
	4.5. Ozone depletion	
	4.6. Acidification	
	4.7. Eutrophication freshwater	
	4.8. Eutrophication seawater	
	4.9. Eutrophication land	
	4.10. Smog formation	
	4.11. Abiotic resource depletion – minerals and metals	
	4.12. Abiotic resource depletion – fossil fuels	
	4.13. Water use	
	4.14. Particulate emissions	
	4.15. Ionizing radiation	
	4.16. Ecotoxicity (freshwater)	
	4.17. Human toxicity, carcinogenic	
	4.18. Human toxicity, non-carcinogenic	
	4.19. Land use-related impact/soil quality	
5. Functional-technical value at the end of the life cycle	5.1. Functional quality at the end of life	
	5.2. Technical quality at the end of life	
	5.3. Degradation at the end of life	
	5.4. Reuse potential at the end of the life cycle	
6. Economic value at the end of the life cycle		

5.3.3.2.3.5 Material Circularity Indicator (MCI) – Not used by asset managers of municipalities at the moment

The Material Circularity Indicator (MCI) is developed by the Ellen MacArthur Foundation and ANSYS Granta [90]. The MCI represents, as a single number, the extent to which the linear use of materials is minimised and the restorative material flows are maximised [90]. Additionally, the MCI considers how long and intensively a material is used compared to a similar industry-average product [90]. The MCI is a value between 0 and 1, where 0 indicates a low circularity level and 1 indicates a high circularity level [90].

The MCI can be calculated in 8 steps. These steps are [90]:

1) The calculation of the virgin feedstock
2) The calculation of unrecoverable waste
3) The calculation of the waste generated in the recycling process
4) The calculation of waste generated to produce any recycled content used as feedstock
5) The calculation of the total amount of waste
6) Calculation of Linear Flow Index, which measures the proportion of material flowing in a linear manner

7) Calculating the utility
8) Calculating the Material Circularity Indicator

The benefit of the MCI is that it represents the circularity in just one number, which makes it easy to compare MCI's. However, this circularity indicator is not used by asset managers of municipalities in the Netherlands at the moment.

5.3.3.2.3.6 Lifespan extension by repairments – Often not explicitly used by asset managers

Timely repairs and preventive maintenance (e.g. rejuvenating cream) can prolong the lifespan of an asphalt road [94]. This can lead to a reduction in raw material usage and costs [94]. Hence, the circularity of the road increases since the R principle of "repair" is used. An indicator of lifespan extension could be the number of years of extended life versus the extra materials needed for lifespan extension.

Indicators that are currently used:

- Percentage of recycled asphalt
- Percentage of biobased binders
- Environmental Cost Indicator (MKI)

List of possible additional circularity indicators according to the literature and interviews:

- The CB'23 platform indicators
- Material Circularity Index (MCI)
- Lifespan extension
- The reduced amount of materials compared to traditional working methods

Need and obstacles to apply more indicators:

- **Need:** Indicators that are less focused on a specific solution, such that other innovations are also stimulated to reach the overall goal. Besides, indicators are needed that express up or downcycling and all the levels of the R-framework; (1) Refuse, (2) Reduce, (3) Reuse, (4) Repair, (5) Refurbish, (6) Remanufacture, (7) Repurpose, (8) Recycle, and (9) Recover energy. The question is how indicators for all these levels can be created, since the focus is at the moment on recycling. Furthermore, the definition of, for instance, reuse needs to be better specified.
- **Obstacles:** Clear definitions are needed, for instance, for reuse and recycling. At the moment, these definitions do not seem to be clear to everyone. Furthermore, more data needs to be collected on material usage in asphalt.

5.3.3.3 Climate Adaptation Indicators

The interviews and policy documents indicate that many municipalities aim to become more climate-adaptive. However, there currently seem to be no widely adopted indicators to measure climate adaptation.

5.3.3.3.1 The need for climate adaptation indicators

As mentioned in Section 3.2.1, climate adaptation is needed since the climate is rapidly changing, resulting in problems like heat stress and flooding. The society needs to be ready to adapt to this changing climate to prevent, for instance, flooding.

Due to the changing climate, the risk of asphalt damage caused by heat, drought, or water is increasing [95]. Heat can cause asphalt to deform and become damaged [95]. Certain materials in asphalt are more sensitive to heat than others [95]. If materials in asphalt expand due to heat, the asphalt may crack [95]. Besides, drought can damage roads in multiple ways. Firstly, it can accelerate subsidence that can cause damage to the asphalt [95]. Secondly, climate change increases the risk of verge and forest fires, which can affect asphalt pavement [95]. Additionally, extreme weather events, such as heavy rainfall, can lead to road flooding [95]. In one of the interviews, it was mentioned that asset managers want to ensure that during heavy rainfalls, their roads remain accessible as long as possible and do not flood so that emergency vehicles can still use the roads.

Furthermore, asphalt is also a significant contributor to the urban heat island effect [96]. This can lead to heat stress, which is a problem in urban areas since heat stress can lead to increased job loss among vulnerable groups, an increase in illness and premature death [15]. Densely graded asphalt concrete has a low albedo and a high volumetric heat capacity, which can cause surface temperatures of 60°C on a hot summer day. According to the literature, cool pavement can be used that is reflective or evaporative to reduce the urban heat island effect [96]. Based on local atmospheric conditions and urban geometry, it should be decided whether to use this mitigation strategy because, in some cases, it can also increase the urban heat island effect [96].

To prevent road damage and heat stress caused by climate change, infrastructure must be designed to withstand changing climate conditions. Therefore, road authorities focus on developing climate-adaptive infrastructure [9]. To strengthen climate adaptation efforts, the Dutch government has introduced two documents: het Nationale Deltaprogramma and de Nationale Klimaatadaptatie Strategie [97] [15] [98].

The National Delta Program is an annual proposal by the Delta Commissioner for efforts in water safety, freshwater supply, and spatial adaptation [98]. According to the National Delta Program, a design-oriented approach, where various possible future scenarios are developed and considered, has proven to be an important tool in dealing with uncertainties such as climate change [98]. Furthermore, the National Climate Adaptation Strategy was established by the Ministry of Infrastructure and the Environment to accelerate existing initiatives and initiate new ones that contribute to a climate-resilient Netherlands [15].

5.3.3.3.2 Definition of climate adaptation

According to the Intergovernmental Panel on Climate Change (IPCC), climate adaptation can be defined as “the process of adjustment to actual or expected climate and its effects in order to moderate harm or exploit beneficial opportunities” [99]. This definition corresponds to the definition used in the National Climate Adaptation Strategy [15]. In addition to climate adaptation, the strategy of climate mitigation can also be applied. Climate mitigation focuses on reducing greenhouse gas emissions to limit climate change [15].

5.3.3.3.3 Indicators to measure climate adaptation

During conversations with the asset manager, it became clear that they consider climate adaptation in their work. This is primarily considered during major road reconstruction projects, rather than during small maintenance. Many interviewees indicated that they lacked clear indicators to assess climate adaptation. Some interviewees suspected that climate change is causing roads to deteriorate more quickly. Other interviewees emphasised that they took water drainage into account in the decisions they made, for instance by using permeable road surfacing or building a foundation under the road that can store water. An indicator for climate adaptation can, for instance, be the volume of extra water that can be stored after a road maintenance project.

In one of the interviewed municipalities, a large project is going on where sensors are used to measure temperature, humidity, and particulate matter before, during, and after maintenance work. This approach aims to provide more insight into the environmental impact of maintenance activities and on how climate-adaptive certain measures are. Indicators can, for instance, be the change in temperature, humidity and particulate matter before and after a project.

Besides, in the literature, there is also limited information on indicators for measuring the extent to which climate adaptation is achieved in asphalt pavement projects. However, a decision-making assessment process for climate adaptation has been identified, which includes the following key steps: (1) understanding the site context and future climate, (2) testing the asset against future climate scenarios, (3) developing, evaluating, and selecting adaptation measures, (4) reviewing additional considerations, and (5) monitoring and revisiting as needed [100]. This framework could be useful when defining relevant indicators.

Additionally, a study identified several indicators applicable to climate change adaptation projects. The most relevant indicators from this study for this research fall under the category of “climate change impact reduction”. These include the following sub-indicators [101]:

1) The project's greenhouse gas reduction capacity
2) Its effect on climate change adaptation capacity and vulnerability reduction
3) The potential for addressing climate-related challenges in specific regions and facilities
4) The ease of technical application, considering local conditions and environmental factors

The study does not clearly define how to score these indicators. It mentions that a rating system can be used with categories such as "very good," "good," "average," "bad," and "very bad" [101]. The exact criteria for these classifications are not specified, leaving room for interpretation.

Furthermore, indicators can be used to get insight into heat stress caused by pavement. Material properties that affect the pavement temperature are: albedo, emissivity, thermal conductivity and specific heat capacity [102]. These material properties are therefore indicators of how cool the road pavement is. Currently, several cool pavement materials can be distinguished such as; reflective pavements, permeable pavements, materials with enhanced heat storage and pavements that can extract heat [102]. Research shows that even though these materials can reduce the surface temperature of the pavement, their effect on air temperature is limited [102]. It appears to be more effective to lower the air temperature by creating shaded areas and planting trees and greenery [102]. Therefore, it is questionable whether it is useful to use material properties as indicators of heat stress.

Indicators that are currently used:

- Currently, there are almost no indicators that are used for climate adaptation

List of possible additional climate adaptation indicators according to the literature and interviews:

- The steps of the decision-making strategy for climate adaptation are all followed (yes/no): (1) understanding the site context and future climate, (2) testing the asset against future climate scenarios, (3) developing, evaluating, and selecting adaptation measures, (4) reviewing additional considerations, and (5) monitoring and revisiting as needed
- Volume increase of water storage (m^3) after doing maintenance
- The average increase/decrease in the surface temperature due to maintenance (°C)

Need and obstacles to apply more indicators:

- **Need:** The is a need for climate adaptation indicators. However, there are almost no SMART goals formulated for climate adaptation. Specific norms are needed to determine if a road is climate-adaptive.
- **Obstacles:** Climate adaptation is influenced by many factors and not only by the type of pavement. Therefore, it is difficult to express the level of climate adaptation of a road.

5.3.4 Product and Process Indicators

The quality of asphalt pavement achieved during construction is linked to the quality of the construction process and the quality of the asphalt mix produced at the asphalt plant. Gaining insight into both product and process quality can help managers to more accurately predict the road lifespan and develop more effective maintenance strategies. Additionally, this knowledge may provide valuable insights into the underlying causes of road failure, enabling more proactive and data-driven decision-making. Currently, product and process quality are often not considered by asset managers in their maintenance planning.

5.3.4.1 The need for product and process indicators

Asset managers aim to construct high-quality roads. However, interviews revealed that many asset managers rarely rely on data from the construction process to assess asphalt quality or to improve maintenance predictions. This is largely due to their trust in contractors to deliver a high-quality road. Currently, road quality is often evaluated at the time of delivery using 100 mm drill cores, which are analysed in a laboratory after the asphalting process is completed [103]. During the asphalting process itself, data on process quality, critical to the final product, is often not collected. It might be beneficial to collect this data to get a better insight into factors that might impact the deterioration of an asphalt road. Based on this data, better maintenance strategies can be set up.

5.3.4.2 The definition of product and process quality

The final quality of an asphalt road depends on the process quality in the asphalt plant and the process quality on the construction site. During the production of asphalt in the asphalt plant, samples are taken to determine the composition, bitumen content and grain distribution in the asphalt, which influences the product quality [103]. Furthermore, the asphalt plant examines the temperature of the asphalt during production and uses gyrator test pieces of which the density is determined and the voids are calculated [103].

Once the asphalt is produced at the asphalt plant, it is used to construct roads. The asphalt construction process can be divided into four stages: the production phase, the transportation phase, the paving phase and the compaction phase [25] [26]. These four phases need to be aligned to prevent discontinuities from occurring in the construction process that can lead to variability and hence lower the quality of the final compacted asphalt layer [27].

The quality of an asphalt road that is reached during the construction of the road depends on the density that is reached during compaction [28]. The asphalt density is mainly dependent on compaction operations [25] [26] and the asphalt temperature at which compaction occurs [25] [26]. The temperature should be as homogeneous as possible during compaction to reach the highest possible quality [26] and the compaction should be homogeneous, avoiding over- or undercompaction [26]. Other factors that influence compaction are environmental conditions (e.g. ambient air temperature, wind speed or rainfall) and material properties [28].

5.3.4.3 Indicators to measure product and process quality

Currently, asset managers hardly use indicators related to the quality of the roads reached during the construction process. Cores with a diameter of 100 mm are often drilled to determine the achieved density [103]. Furthermore, in situ measurements are made to measure the skid resistance and the evenness of a road after its construction [103]. However, this data is often not used by asset managers as a basis for their prediction of needed maintenance. Besides, a core can give a biased picture of the quality of the road, as it is a local measurement, and the quality can vary over the road section.

It might be beneficial to use data about the whole asphalt production and construction process that influences the quality of the road. Indicators to measure the asphalt quality reached during the construction of roads can be related to the four phases of the construction process: the production phase, the transportation phase, the paving phase and the compaction phase. First of all, monitoring indicators can be used regarding the production phase at the mixing plant such as; asphalt aggregate ratio, grading, asphalt weight, mixture temperature, mixing time, silo weight and discharge temperature [104]. Besides, for the transportation phase, indicators related to the transport vehicle are important to consider such as the loading time, the loading place, the transportation route, the transportation time and the transportation speed [104]. Furthermore, indicators can be related to the paver; the paving track, the paving speed, the paving time and the asphalt temperature [104]. Lastly, indicators can be used that relate to the rollers; the rolling speed, rolling track, rolling times, asphalt temperature, the reached density and vibration frequency [104].

The asphalt temperature should be kept as homogeneous as possible, and it can, for instance, be measured using infrared sensors [26]. Additionally, the rolling track and the number of roller passes can be monitored using GPS technology [26]. Since GPS equipment is expensive, research is also being conducted on alternative methods, such as tracking the rolling path with infrared thermography [105].

This data can be used to get an indication of potentially more vulnerable spots in a road [106]. This knowledge allows for more proactive road inspections and improved maintenance strategies [106]. For example, if large temperature differences occur during the construction process in a particular road section, this could be an indication that this spot is more vulnerable in the future, which can be taken into account by asset managers in their maintenance strategy. Furthermore, a compaction contour plot can be used to visually indicate the number of rolling passes per location [106]. This can also give an indicator of the quality achieved during the construction process.

However, during the validation workshop, it was noted that indicators for process quality are currently only available after the road construction has been completed. Participants emphasised that it would be more beneficial to obtain this data during the construction process itself, as this would enable timely corrective actions.

Indicators that are currently used:

- Density based on cores with a diameter of 100 mm
- In-situ skid resistance measurements
- In-situ evenness measurements
- Temperature measurements of the asphalt in the asphalt plant

List of possible additional process and product quality indicators according to the literature and interviews:

- Temperature differences on a road section during the paving process
- Number of roller passes during compaction

Need and obstacles to apply more indicators:

- **Need:** Data to get a better insight into the quality of the asphalt and into risk areas in the asphalt pavement, so that better predictions can be made on the lifespan of the road.
- **Obstacles:** More data should be collected on the construction process in collaboration with contractors. To do this, the contractors must be willing to collect this data. If the data could be used against them, they are probably less willing to share this data. Moreover, this data should be collected during the construction process, because at that moment corrective actions can still be made.

5.4 MONITORING AND DATA COLLECTION

Data collection and monitoring are important for asset managers and are needed to measure the indicators mentioned in Chapter 5.3. Besides, according to multiple interviewees, it is crucial to record which decisions are made regarding infrastructure assets. Multiple asset managers struggled with the fact that their predecessors did not report the work they did or the choices they made. They emphasised that it is important to keep data up to date and report everything you do as an asset manager.

Some interviewees indicated that they have sufficient data to make well-informed decisions regarding asset management. Nevertheless, several asset managers expressed the need for additional data, particularly concerning verges, surrounding areas, underground conditions, road behaviour, and the expected residual life of roads. Information about developments in the surrounding area often requires input from other municipal departments or external stakeholders, such as utility companies. Moreover, accurately predicting the residual life of a road requires falling weight deflection measurements. These measurements are costly, which limits their use by infrastructure asset managers.

From the interviews, it could be concluded that the data about the assets can be categorised into three categories; general information about the road, condition data and sustainability data. However, data on sustainability is often missing.

5.4.1 General information

The general information[4] that is important for asset managers is related to aspects such as:

- The roads that the asset managers own (segment ID, location, direction, number of lanes, etc.);
- The functions of the road;
- The traffic intensities on the roads;
- The materials a road is made of;
- The compositions and dimensions of the roads;
- Environmental conditions;
- Construction dates of the roads;
- The maintenance history of the roads (timing and type of maintenance).

In interviews with asset managers, it appeared that most of this data is already available to them. However, certain details, such as construction dates or road composition, are sometimes unclear due to a lack of documentation in the past. Additionally, some asset managers noted that performed road maintenance is not always well-documented. To improve data collection, many asset managers are developing a road passport to track information, such as the materials used in a road. Some municipalities are also using technologies like radar systems to gain better insights into, for instance, the composition of their roads. By recording this type of data, it is possible, for example, to see in which roads similar materials are used if it turns out that a certain type of asphalt deteriorates faster than planned. With this information, better maintenance strategies can be created.

5.4.2 Condition data

Besides the general information, data is needed to measure the condition of roads. At the moment, most of the municipalities are conducting the visual CROW inspection once a year or once every two years to get insight into the condition of their roads. Besides, the municipalities are also conducting additional visual inspections during the year themselves to detect damage.

According to most interviewees, the available data provides a reliable understanding of road conditions, but more detailed and objective data would be better. One of the interviewees finds it difficult that the CROW inspection results are documented as a score. As an asset manager, he also values seeing the actual condition of the road and its surroundings. To address this limitation, municipalities can also learn from, for instance, provinces. In the interviewed province, cameras are used for the inspection of roads. Afterwards, this camera footage is analysed with the help of the visual CROW method. The results of the inspection are then visualised in a map. Users can click on specific points in the map to view the corresponding camera images for that location. This method integrates visual documentation with CROW scoring, enhancing the accessibility and interpretability of the information. The province opted for map-based visualisation because it offers more intuitive insights than traditional data presentation formats, such as Excel spreadsheets.

Furthermore, some of the interviewed municipalities also use the number of complaint reports as an indicator of road quality and citizen satisfaction. When a significant number of well-founded complaints are received about a specific road, the municipality assesses the situation and decides whether action is needed.

Currently, most inspections for municipal roads are carried out visually. However, conversations with asset managers revealed that new inspection technologies are currently being tested. For

[4] General information relates to data on standard features for each road such as road geometry, materials, location of the road and the function of a road

example, one of the interviewed municipalities uses laser scanners to inspect roads, while another has started conducting inspections with cameras. During an interview with an expert in the field of asset management, it was mentioned that it might be beneficial for asset managers to collect more detailed information and also measure more data. The reasoning behind this is that measurement data can be better compared and monitored over the years, and that one visual score for a road section of 100 meters measured based on the CROW guidelines is not always representative. However, the costs of collecting more detailed data compared to the benefits it brings need to be considered.

All data collected during inspections, along with general information about the roads, is often stored in a central database.

5.4.3 Sustainability data

The interviews revealed that data related to sustainability is often not systematically collected. When such data is gathered, it is frequently done in a non-standardised and ad hoc manner. Uniform data collection is essential for facilitating comparisons across projects and for evaluating the performance of asset managers in relation to their sustainability goals. In the absence of consistent data collection, it becomes impossible to monitor whether sustainability objectives are being achieved.

Current data collection methods municipalities:

- Visual data collection during CROW inspection
- Tests with new data collection techniques are currently done such as laser scanners and cameras
- Complaints of citizens
- Measurement data is used in specific situations

Desired improvement in data collection methods:

- Better documentation of the reasoning behind the choices of asset managers (e.g. the reason that a project is postponed)
- More data on the underground, verges, behaviour of the roads, the surrounding area and the expected residual lifespan of roads
- More detailed condition data, since data is now often based on road sections of 100 meters
- More data needs to be collected related to sustainability

Difficulties in reaching the desired situation:

- The benefits of the desired data collection methods are outweighed by the extra resources needed to obtain all the data
- The working method of asset managers needs to be changed

6 RESULTS – THE DESIRED FUTURE SITUATION

This chapter outlines the desired future context in which asset managers operate. It begins by describing their envisioned future tasks, based on the insights from interviews and the validation workshop, and it identifies the goals that asset managers in the future need to pursue (see Section 6.1). Subsequently, Section 6.2 discusses the aspects that asset managers need to include in their future decision-making processes to achieve their goals. Next, Section 6.3 examines the indicators that need to be used in the future by asset managers based on the interviews and validation workshop. Lastly, Section 6.4 explains the monitoring and data collection techniques which are needed in the future to reach the goals of asset managers and to improve the strategic decision-making process.

6.1 THE ROLE OF FUTURE INFRASTRUCTURE ASSET MANAGERS & THEIR GOALS

This section outlines the envisioned future role of asset managers and the objectives they will be required to address in the future.

6.1.1 The goals of the asset manager of the future

Based on the interviews, it can be concluded that asset managers must adapt their approach to effectively achieve all the objectives outlined in policy documents, including those related to safety, health, climate adaptation, image, economy, resilience, biodiversity, accessibility, citizen participation, and sustainability [50] [51] [52] [53]. Currently, asset managers primarily focus on goals associated with technical quality and cost efficiency. To also meet sustainability-related objectives, this gap between practice and policy documents should be closed. The sustainability goals mentioned in policy documents should become SMART (Specific, Measurable, Achievable, Relevant and Time-bounded) and a shift in mindset is required, moving beyond a purely technical perspective to incorporate social and environmental considerations.

6.1.2 Changing role of asset managers according to the current asset managers

What the role of an asset manager will look like in the future is still uncertain, but the interviewees envision that their way of working will change in the future. Many believe that personal, local knowledge will always be essential, as not all decisions can be driven by data alone. However, data is expected to play an increasingly important role in supporting asset managers in making informed choices.

During the interviews, the interviewees were asked how they envision the future role of asset managers. The interviewees already observe a shift in the role of asset managers. Traditionally, the role of road asset managers was predominantly technical. However, several respondents mentioned that the focus is increasingly shifting towards more societal aspects. The introduction of systems such as urban heating networks and the growing demand for sewerage system maintenance necessitates better alignment between road maintenance and the maintenance of other infrastructure assets to prevent unnecessary construction work that causes hindrance to citizens and results in unnecessary expenditures. Consequently, the need for more integrated working methods is increasing, requiring enhanced communication and information exchange with the asset managers of other assets.

Besides, one interviewee envisioned that the asset manager of the future needs to have GIS-related skills, enabling asset managers to conduct more spatial analyses to gain deeper insights into the factors influencing road deterioration. Another interviewee, an expert in the field of asset management, mentioned the potential benefits of collecting all data of every municipality in a central environment, such as GIS, so that data becomes exchangeable. This would not only facilitate data exchange but also allow for the integration of information from other assets and projects within the same geographic area.

The interviewees also emphasise that it is still important to have practical asset managers with local knowledge in the future. While the use of data can support better decision-making, several respondents warned for an excessive reliance on data, as an overabundance of information may complicate decision-making processes rather than simplify them. The asset managers of the future need to be critical and need to understand the results created by, for instance, artificial intelligence.

Furhermore, asset managers need more information and data to improve their decision-making process and to reach sustainability goals. Decision-support tools are essential for balancing multiple goals, including technical quality, cost-efficiency, circularity, climate neutrality, and climate adaptation. Moreover, the decision-making process of asset managers needs to change from being reactive to being proactive. By becoming more proactive, material consumption and costs can be reduced [94]. To become more proactive, extra data is needed on, for instance, factors that influence the degradation of roads. Predictive models are needed to estimate road lifespan and generate various maintenance scenarios, outlining their respective advantages and disadvantages.

6.1.3 Expected future developments influencing the work of asset managers

It is expected that technologies such as machine learning, artificial intelligence, and the Internet of Things, along with process innovation, will have an impact on asset management [107]. In addition, it is expected that the possible introduction of connected and automated vehicles in the future will impact road maintenance [108]. According to Correia et al. (2023), the road surface quality is critical for the optimal functioning of connected and automated vehicles [108]. If the quality of the road is not sufficient, due to, for instance, potholes or poorly made joints, this can negatively impact the detection system of the cars [108].

Nevertheless, connected and automated vehicles can also be utilised to collect more real-time data, which can be used by asset managers [108]. This data has the potential to transform asset management from a static environment into a dynamic environment [108]. Besides, this might reduce the costs of collecting relevant data.

Furthermore, it became apparent in the interviews with asset managers that the introduction of, for instance, a city heating network will also impact the planning of road maintenance. It appeared from the interviews that utility companies are increasingly influencing the planning of road maintenance.

6.2 DECISION-MAKING PROCESS

The decision-making process of asset managers must change from a predominantly reactive approach, focused primarily on technical indicators related to goals such as safety, appearance, durability, and comfort, toward a more proactive strategy that fully integrates sustainability objectives. Without this shift, achieving sustainability goals will remain unlikely. The main priorities should include, based on what is found in literature, reducing greenhouse gas emissions, material consumption, and the use of abiotic primary resources while simultaneously extending asset lifespan, enhancing preventive maintenance, improving resilience to climate change, and maintaining high technical quality (see Figure 7). Consequently, these factors must be systematically incorporated into the decision-making framework.

The situation that needs to be achieved	Linked goals	Examples that could contribute to achieving the desired situation
Emissions CO_2, CH_4, N_2O, HFK, SF_6, PFK´s ↓	Climate neutrality and climate adaptation	Innovations such as: • Lower production temperatures • Preventive maintenance • Storing emissions • Generating energy with road • Asphalt plants operating on green electricity • Using alternative materials
Material usage ↓	Circularity	Innovations such as: • Asphalt that is reusable (e.g. modular asphalt used first on a motorway, then on a provincial road, and then on a municipal road etc.) • Recycling • Preventive maintenance of road (prevention is better than cure) • Self-healing asphalt
Lifespan ↑	Circularity andclimate neutrality	Innovations such as: • Self-healing asphalt/ asphalt with longer life span • Preventive maintenance • Models that can better determine the life of the road and provide warnings when they expect maintenance to be needed
Abiotic materials ↓	Circularity	Innovations such as: • Biobased binders • Alternative materials made from biotic substances
Preventive maintenance ↑	Costs, circularity, safety and product quality	Innovations such as: • Rejuvenation cream/ oil • Predictive models about when damages are likely to occur on the road • Real-time data collection • Improved quality control using technologies such as GPS and infrared thermograhpy
Resilience to climate change ↑	Climate adaptation	Innovations such as: • Cool asphalt • Asphalt with a water buffer
Technical quality =/↑	Appearance, safety, comfort and climate neutrality	Innovations such as: • Asphalt with a longer lifespan / self-healing asphalt • Preventive maintenance • Models that can better estimate when maintenance is needed

Figure 7 - A desired situation (derived from the interviews and literature)

In Figure 8, the decision-making process for the asset manager of the future envisioned by the author of this thesis, based on the interviews with asset managers, is shown. This decision-making process can be followed for every road by asset managers. To select the best maintenance strategy, the goals mentioned in Figure 7 need to be taken into account and indicators are needed to measure to what extent these goals are reached (see Section 6.3). This decision-making process deviates from the current decision-making process followed by asset managers such as described by the CROW [12], since it includes preventive maintenance and considers sustainability goals.

The decision tree includes a decision step for preventive maintenance and includes sustainability goals. Moreover, there is flexibility in the decision tree, allowing municipalities to set their own criteria for when an answer should be "yes" or "no" based on their policy. Furthermore, the decision point in the decision tree does not prescribe exactly how a choice should be made. This is because the decision-making process also depends on the available data and tools. Over the years, municipalities should improve these decision-making moments by using better tools and data.

Besides, the conversations and interviews conducted revealed that, in the future, it will become increasingly important to align projects from different disciplines. The asphalt construction projects need to be aligned with, for instance, maintenance of the sewerage system, the construction of a municipal heat network and maintenance of the electricity grid. Therefore, this is also included in the decision tree as a separate decision moment.

Asset management decision tree

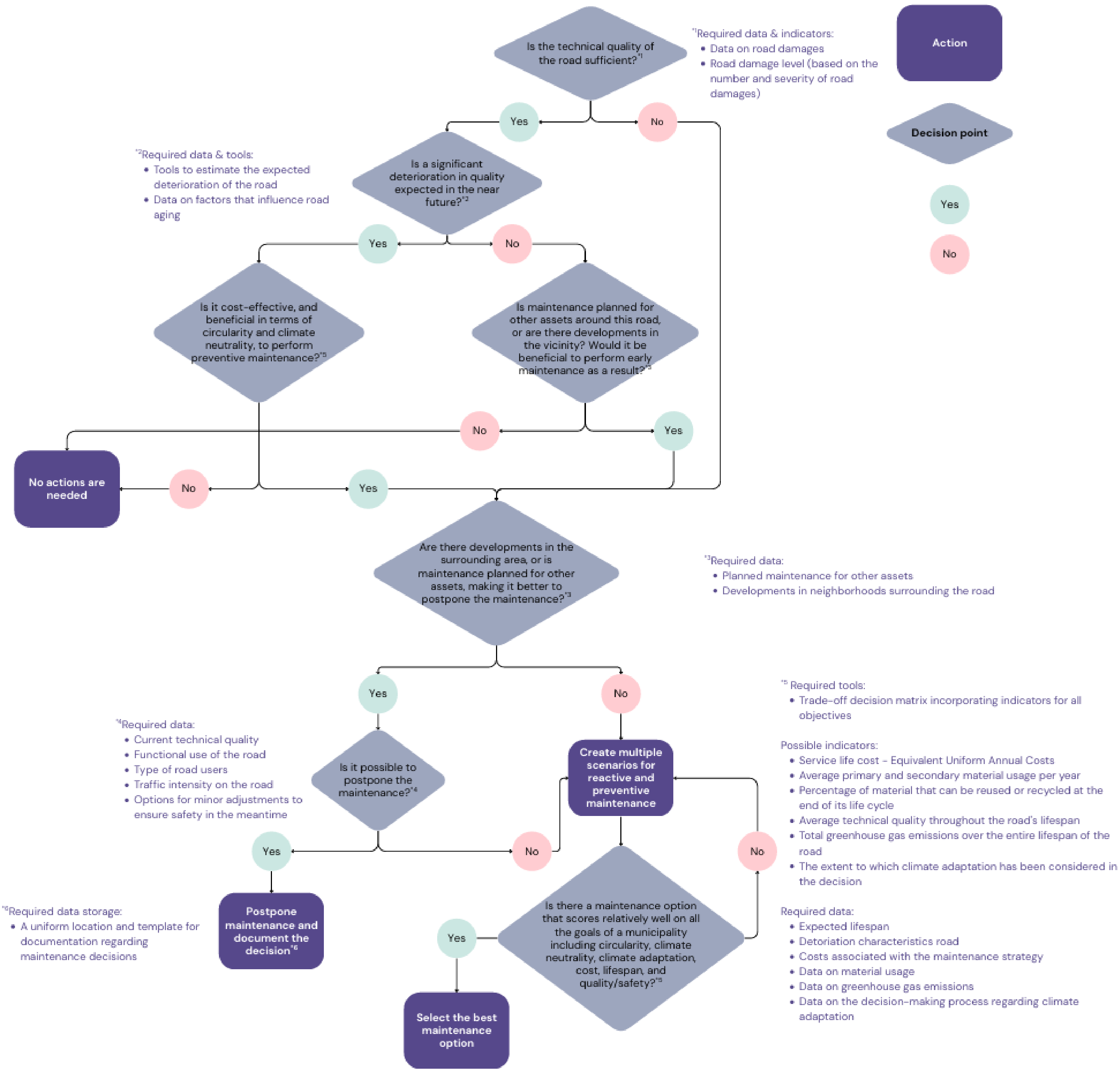


Figure 8 - Decision tree

6.3 INDICATORS

Based on the interviews, it can be concluded that more specific and objective indicators are required to assess whether asset managers' goals are being achieved. As mentioned in Section 6.2, these indicators are also needed in the decision-making process of asset managers. This section outlines the key indicators needed for the future and identifies the barriers that must be overcome to effectively measure them.

6.3.1 Technical indicators

The technical indicators currently used are often the indicators formulated in the CROW guideline for global visual inspections [48] and give a general insight into the road condition, as mentioned in Section 5.3.2.1. These technical indicators are often partly subjective and lack details, such as the exact locations of the damages according to the interviewees. This finding was validated during the validation workshop. These indicators give insight into when reactive maintenance needs to be done. However, in the future desired situation, preventive maintenance should also be done. Since, according to the literature, preventive methods can be significantly more sustainable than conventional pavement rehabilitation, and it can be more cost efficient [109] [94] [110]. Therefore, there is a need to have more detailed and objective indicators and to have more insight into the degradation and expected technical lifecycle of a road to plan preventive maintenance. The interviewees also mentioned several times that they need more data on the expected technical lifecycle of their roads to improve their maintenance strategies.

The interviews revealed that more objective data and indicators could be obtained through measurements such as the International Roughness Index, the rut depth, the Mean Profile Depth, and the skid resistance (as explained in Section 5.3.2.1.3). Most of these measurements are still expensive. Therefore, it might be beneficial to stimulate innovations to make data collection less expensive. Such as data collection with mobile phones or standard cars. Currently, a test is already going on at Rijkswaterstaat to monitor the road condition with the sensors installed in standard cars; the ROMO project [111].

Moreover, current inspection data is often not visualised on a map. Some of the interviewed asset managers indicated that it would be beneficial to present inspection data on a map where different types of damage can be selected. The map should display the location and severity of the damage. Additionally, several asset managers suggested that incorporating images of the damage and its surrounding environment would be valuable. This would allow users to visually assess the damage when selecting a specific issue on the map, which would allow asset managers to make better decisions and get a better overview of the condition of their assets.

Furthermore, the interviews revealed that it would be beneficial for asset managers to understand how damages evolve over time. A damage that remains stable for an extended period is often assigned a lower priority than one that deteriorates rapidly. Monitoring such trends requires data collected over a longer time span. This, again, necessitates improved data collection techniques.

6.3.2 Cost indicators

During the interviews, it was found that asset managers primarily focus on investment costs, while the full life cycle costs of infrastructure are often overlooked. Incorporating a life cycle cost approach in road asset management would enable a more strategic and cost-effective maintenance plan. At the moment, it might be the case that suitable solutions are overlooked since the initial investment costs are high, while it might be the case that the life cycle costs of this option over the whole life cycle are low.

However, this requires asset managers to adopt a more long-term perspective and to learn more about lifecycle costs and methods and indicators to calculate and express the life cycle costs, such as the Equivalent Uniform Annual Costs (see Section 5.3.2.2). It must be noted that in these types of techniques, assumptions[5] need to be made, which should be as accurate as possible. For these assumptions, data is needed on, for instance, the deterioration of roads and the extent to which preventive maintenance prolongs the life span of a road. Besides, a clear definition should be formed of what the lifespan of a road is. In the future, we need to move away from these assumptions, and these assumptions need to become as accurate as possible by using data.

At the moment, it sometimes seems to be difficult to get a budget for preventive measures such as applying rejuvenation crème, because the roads on which this is applied are in good condition and are not in the planning of maintenance [94]. However, investing in a preventive measure such as rejuvenation crème can reduce high costs in the future and can be more cost-effective over the lifecycle [94] [110]. Besides, by using preventive measurements, the average performance of a road over its lifetime will probably be higher, which increases safety and driving comfort [109]. Moreover, according to the literature, preventive methods can be significantly more sustainable than conventional pavement rehabilitation [109]. Therefore, the focus should shift towards a situation where the whole life cycle is considered to enable more strategic decision-making.

Moreover, it might be valuable to assess the social and environmental benefits derived from a project in the future, as explained in Section 5.3.2.2.3.5. This method, however, has not yet been widely adopted, as there is no guideline regarding which social benefits should be included in the calculation and how they can be quantified in monetary terms. Despite these challenges, further exploration and experimentation with this method might be worthwhile, as it could reveal instances where the initial investment costs of a particular option may be higher, but where significant social costs are effectively mitigated.

Besides, it will always remain important for asset managers to create insight into the expenses since they have to be transparent.

6.3.3 Climate neutrality indicators

Indicators used by asset managers to assess climate neutrality currently focus primarily on specific solutions, such as the use of electric equipment. This approach may provide a misleading result, as it does not necessarily reflect overall emission reduction. Instead, it would be more effective to use solution-neutral indicators that offer a direct measure of climate neutrality.

One potential approach is to assess emissions of specific greenhouse gases. Many asset managers currently rely on the Environmental Quality Indicator (MKI) for this purpose [82]. However, the MKI does not directly quantify reductions in CO_2 or other emissions, making it less transparent in assessing actual climate impact. Moreover, in multiple conversations, it appeared that many stakeholders found it difficult to interpret the MKI value. Besides, the extra fuel consumption of road users due to degradation in road quality is not considered in the Product Category Rules (PCR) [81] and hence the MKI. A more detailed indicator for climate neutrality could improve decision-making and facilitate clearer communication of climate neutrality. Therefore, there is a need to move away from the MKI and to use indicators in the future that give a better indication of climate neutrality.

An indicator that, for instance, can be used for climate neutrality is the sum of all greenhouse gas emissions expressed in CO2 equivalent [79], since this indicator gives insights into the global warming potential of the greenhouse gases, which directly provides insight into climate neutrality. This indicator can also be split into different greenhouse gas emissions. To determine

[5] Assumptions need to be made related to aspects such as the interest rate, the moment of future maintenance and the costs related to this maintenance.

all the greenhouse gases during the life cycle of a road, a method such as the PCR is needed in the future to calculate all the emissions, but this method might need to be more accurate than the PCR.

6.3.4 Circularity indicators

Circularity indicators in the asphalt sector predominantly focus on recycling rates and the incorporation of bio-based binders. However, these indicators do not fully capture the overall degree of circularity and are applied ad hoc. A more comprehensive assessment is required, incorporating additional indicators that provide a more detailed and comprehensive evaluation of circularity.

Current indicators primarily focus on solutions such as recycling to achieve a circular economy. However, in a circular economy, additional factors also need to be considered, such as the quality and functionality of materials in subsequent life cycles. To ensure a truly circular approach, all components of the R-framework should be integrated into circularity indicators: (1) Refuse, (2) Reduce, (3) Reuse, (4) Repair, (5) Refurbish, (6) Remanufacture, (7) Repurpose, (8) Recycle, and (9) Recover energy [88]. The implementation of this framework requires clear and standardised definitions for each category. Since definitions seem to vary at the moment, when looking at the literature and based on answers given by asset managers during the interviews. During the validation workshop, participants confirmed that asset managers currently have differing definitions of circularity, which hinders progress toward achieving circularity goals. In the future desired situation, all municipalities need to have a standard and uniform definition for circularity to better monitor and guide the achievements of the goal to become fully circular by 2050.

Projects, in the future, should strive for the highest level of circularity as outlined in the R-framework to reach the goal of becoming fully circular by 2050. Rather than focusing solely on material recycling, it might be beneficial to also encourage contractors to create innovations that enhance circularity, such as modular road designs that can be relocated and reused. Additionally, indicators should be developed to incentivise innovations aimed at extending road lifespans. The longer a road remains in use due to (preventive) maintenance, the greater its contribution to circularity. Furthermore, in the desired future situation, there are no obstacles such as calculation rules and regulations that are solely based on traditional processes and hinder circularity. During the workshop, it was mentioned that the calculation rules and regulations are currently based on traditional working processes, which hinders the achievement of the circularity goals.

In a conversation with an expert in the field of asset management, it was suggested that improving circularity in infrastructure projects requires municipalities to collect more detailed information about the materials used in road construction. This aligns with Platform CB'23, which has developed a guideline for creating material passports in the construction sector to promote circular practices [112]. Additionally, better alignment of maintenance and reconstruction plans across projects could significantly contribute to circularity. For instance, materials recovered from one project could potentially be reused in another, thereby reducing waste and promoting more sustainable resource use. Therefore, in the future desired situation, data collected on the construction materials of roads is collected in a standardised manner for each road construction project.

6.3.5 Climate adaptation indicators

Currently, there are very few indicators available for asset managers to measure climate adaptation, despite many policy documents that emphasise the importance of incorporating climate adaptation. This seems to be caused by the fact that climate adaptation depends on multiple factors, and it is a relatively new goal. Furthermore, there are also almost no SMART definitions found for the climate adaptation goals of municipalities in policy documents at the moment. This corresponds with the findings of the interviews and the validation workshop. This makes it difficult to measure the extent to which climate adaptation is reached. Many of the municipalities interviewed do want to achieve goals regarding climate adaptation, but do not know how to draw up indicators for this.

The first step in addressing this issue is to establish SMART climate adaptation goals. These can be goals related to how well roads can withstand heat, flooding or problems created by drought, since in literature it is mentioned that it is expected that in the future, more extreme heat, drought and rainfall are expected due to climate change [95] [15]. Besides, it can be indicators that focus on how much roads contribute to, for instance, heat stress or water drainage. For example, targets could be defined in terms of the maximum surface temperature that asphalt pavement can reach on a hot summer day or the allowable frequency of road closures due to flooding because of heavy rainfall. During the interviews, it was found that without clearly defined and measurable goals, it is difficult to develop meaningful indicators. Once clear and measurable goals are specified, appropriate indicators can be designed to assess whether climate adaptation objectives are being met. Subsequently, a plan can be developed for collecting the data required to operationalise the identified indicators.

6.3.6 Product and process quality indicators

The interviewed asset managers are currently not using indicators that are related to product and process quality achieved during the road construction process. Only product quality measurements are done by assessing drilled cores, with a diameter of 100 mm, after construction [103]. However, it can be useful for the asset manager to have more detailed information about the quality during the road construction process so that they can better monitor possible risk areas and adjust their maintenance accordingly [106].

Therefore, it could be useful for future asset managers to consider incorporating data on the road construction process in their decision strategy for maintenance. For example, information on temperature homogeneity or areas of over- and under-compaction could provide valuable insights into the quality of the asphalt pavement [113]. Collecting this data requires mutual trust between contractors and clients, as well as clear agreements on how construction process data will be used. Besides, during the validation workshop, it was emphasised that the process data and indicators should already be available on the construction site to enable contractors to take corrective actions during the construction process. This aligns with research on real-time pavement operation support systems, which shows that real-time data enables operators to make more informed decisions during asphalt construction and hence improve the product and product quality [113].

Furthermore, a conversation with an expert in the field of asset management revealed that product quality is a crucial consideration when incorporating new types of asphalt mixes. The quality of the materials directly influences the lifespan of the road and plays a role in estimating future maintenance requirements. If a new mix containing, for instance, recycled materials demonstrates lower performance compared to a conventional mix, it raises the question of which option ultimately offers greater value and sustainability over the asset's lifecycle.

6.4 Monitoring and data collection in the future

This section outlines the additional data that is required in the future to measure if the goals of asset managers are achieved. This data that is expected to be required in the future is based on insights from the interviewees, the reviewed literature and the author’s reflections on the discussions conducted with asset managers and experts in the field of asset management. In Figure 9, a list of data that can potentially be collected in the future is given.

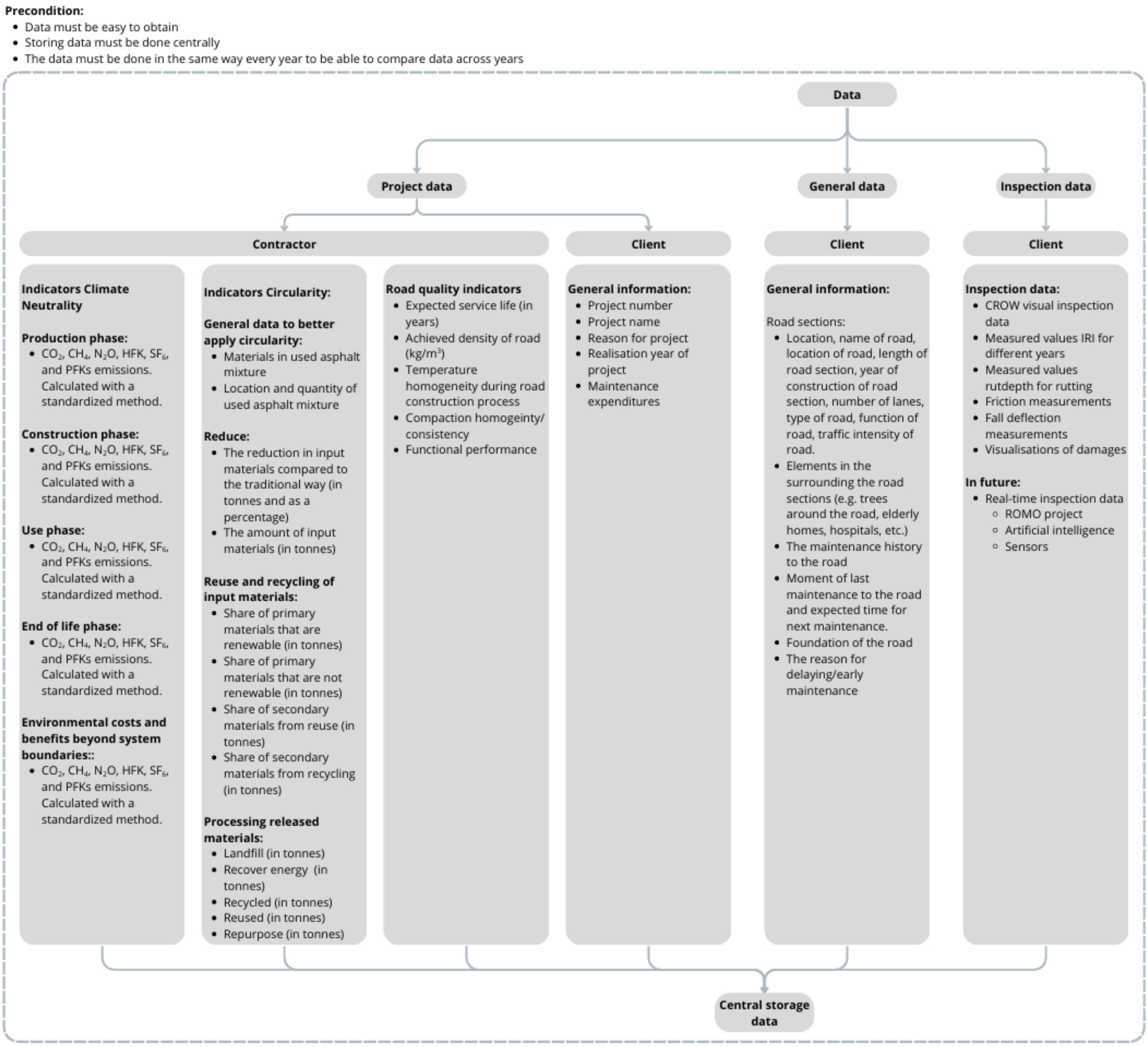


Figure 9 - Potential strategy data collection

6.4.1 General information

A large amount of general information is already available for asset managers, according to the interviewees. However, certain details, such as construction dates or road composition, are sometimes unclear due to a lack of documentation in the past. Additionally, some asset managers noted that performed road maintenance is not always well-documented. To improve data collection, every asset manager should develop something like a road passport in the future to track information, such as the materials used for a road, the moments that maintenance has taken place and which type of maintenance is performed at that moment. Based on this data, better maintenance strategies can be created.

Based on the interviews, it can be concluded that general information, such as the year of construction, type of construction, materials used, historical data and maintenance records, is essential in the future to enable preventive maintenance and to make better predictions about the required maintenance. In the future desired situation, all this data is collected.

6.4.2 Condition data

In the future, road condition data should be more detailed, with precise recording of damage locations. Many interviewees anticipate that future inspections will be carried out using advanced technologies such as cameras and scanners capable of detecting damage. According to one interviewee, this approach could enhance the objectivity and efficiency of inspections. Such developments are considered essential for the creation of more effective maintenance strategies. The desired long-term scenario is real-time monitoring of road conditions.

Interviews revealed that some municipalities are already using LiDAR, radar, lasers, sensors and cameras to inspect their roads. One interviewee suggested that similar data collection techniques could be installed on cars scanning number plates to check if owners have paid for parking in a specific spot. There is even a test going on at Rijkswaterstaat to monitor the road condition with the sensors installed in standard cars; the ROMO project [111]. In this project, multiple municipalities are also participating to investigate to what extent they can use this data [111].

One of the interviewees mentioned that they use laser scanners to inspect the main roads since this is a safer inspection method. This is a safer inspection method because inspectors do not have to stand on the verge of a busy road. Furthermore, fewer inspectors are needed for this method, and inspections can also be carried out at night. However, these inspections cannot be carried out on small roads and roads with low traffic speeds. In the future desired situation, there are techniques that can record this type of data also at lower speeds and on smaller roads.

Besides, one of the interviewees mentioned that inspections can be conducted with a drone, which visualises a road as a point cloud. Inspection done with drones might also be beneficial in the future as it not only provides detailed information about the road itself but also captures additional data on the surrounding environment and the precise dimensions of the road. This tool is not often used yet. In the future desired situation, these types of tools are used to get more detailed information on road conditions while not hindering traffic.

In Sweden, there are already efforts to combine new inspection methods with artificial intelligence, aiming to enable preventive maintenance, increase cost-efficiency, and minimise the environmental impact of road maintenance [114]. The interviews also indicated that some road authorities in the Netherlands want to adopt more preventive maintenance, although, at present, most maintenance is still carried out reactively. Besides, in the interviews, it was mentioned that artificial intelligence is not often used yet to detect damages from video footage, since the results are according to one of the interviewees not reliable enough at the moment. It might be useful to use artificial intelligence in the future to detect damages from video footage if artificial intelligence is further developed and more accurate. This will save much time and can reduce the inspection costs.

Furthermore, it could be desirable to have more real-time data so that action can be taken as soon as problems arise and better predictions can be made about how a road is deteriorating. For example, sensors on normal cars, which are used daily, could be useful in collecting more real-time data. However, a challenge mentioned during one of the interviews is that the location data of a normal car is not precise, which can result in inaccurate data. To the best of the author's knowledge, there are currently no municipalities where real-time data is collected on a daily basis, and innovations are still needed to move towards this situation.

Lastly, more detailed information might be needed about the road construction process in the future, since this influences the quality of asphalt according to literature [113]. At the moment, data on factors such as temperature homogeneity and the number of rolling passes are rarely collected, according to the interviewees. When combined with environmental variables, such as ambient temperature during construction, this type of data could potentially support more accurate predictions regarding future road maintenance needs. In the future desired situation, this data is collected and already available on the construction side. By making the data already available on the construction side, corrective actions can still be taken.

6.4.3 Sustainability data

To achieve relatively new objectives, such as those related to sustainability, more data is needed. This includes information on the materials used in road construction, emissions produced throughout a road's lifecycle, and the extent to which a road is climate-adaptive. However, questions remain regarding who should be responsible for collecting this data and what methods would be most effective for doing so.

It is concluded, based on what is found in the literature and in the interviews, that it could be beneficial to collect at least data on the following aspects in the future to measure if the sustainability goals are reached:

- Data on material input:
  - The amount of primary materials that are renewable
  - The amount of primary materials that are non-renewable
  - The amount of secondary materials that are reused
  - The amount of secondary materials that are recycled
- Data on material output:
  - Available material for next cycle; reuse and recycling
  - Lost material for the next cycle; energy recovery and landfill
- Data on emissions:
  - Energy consumption in the asphalt plant per ton of asphalt
  - Emissions during the whole life cycle of the road
- Data on costs and value:
  - The life cycle costs
  - The value of a road
- Data on climate adaptation:
  - Surface temperature road
  - Water storage capacity around the road
  - Water drainage capacity around the road
  - Vulnerability of roads to heat, flooding and drought
- Data on social aspects:
  - A healthy living environment, e.g. noise, the emission of harmful substances and accessibility for disabled people.

In the future, it would be desirable to have a standardised data entry template to enable municipalities to collect project data in a uniform manner, thereby facilitating comparability across different scenarios.

7 RESULTS – REQUIRED CHANGES

Figure 10 provides a summary of the key aspects identified in the literature and interviews that asset managers must consider in their work. Additionally, it presents an overview of the current situation as explained in Chapter 5 and outlines the desired future state as described in Chapter 6.

Figure 10 - Current and desired situation related to asset management

To move towards the desired situation, multiple steps can be taken. Moreover, as one interviewee noted, a frontrunner is essential, someone who actively supports and believes in new approaches to asset management. Without such leadership, it is unlikely that current practices will evolve, which will hinder progress toward reaching broader goals such as the Sustainable Development Goals (SDGs).

To more effectively achieve the objectives of asset managers, several changes are needed. This section describes which changes can be made to reach the desired situation. These changes are based on the outcomes of both the interviews and the validation workshop and are further shaped by the author's interpretation of these findings. Given that asset management involves a 'wicked problem', there is no single solution to the problem [13]. The proposed changes represent one of several possible approaches, constructed to offer a well-informed route toward the desired future state. In Figure 11, changes that can be made to reach the desired situation are listed.

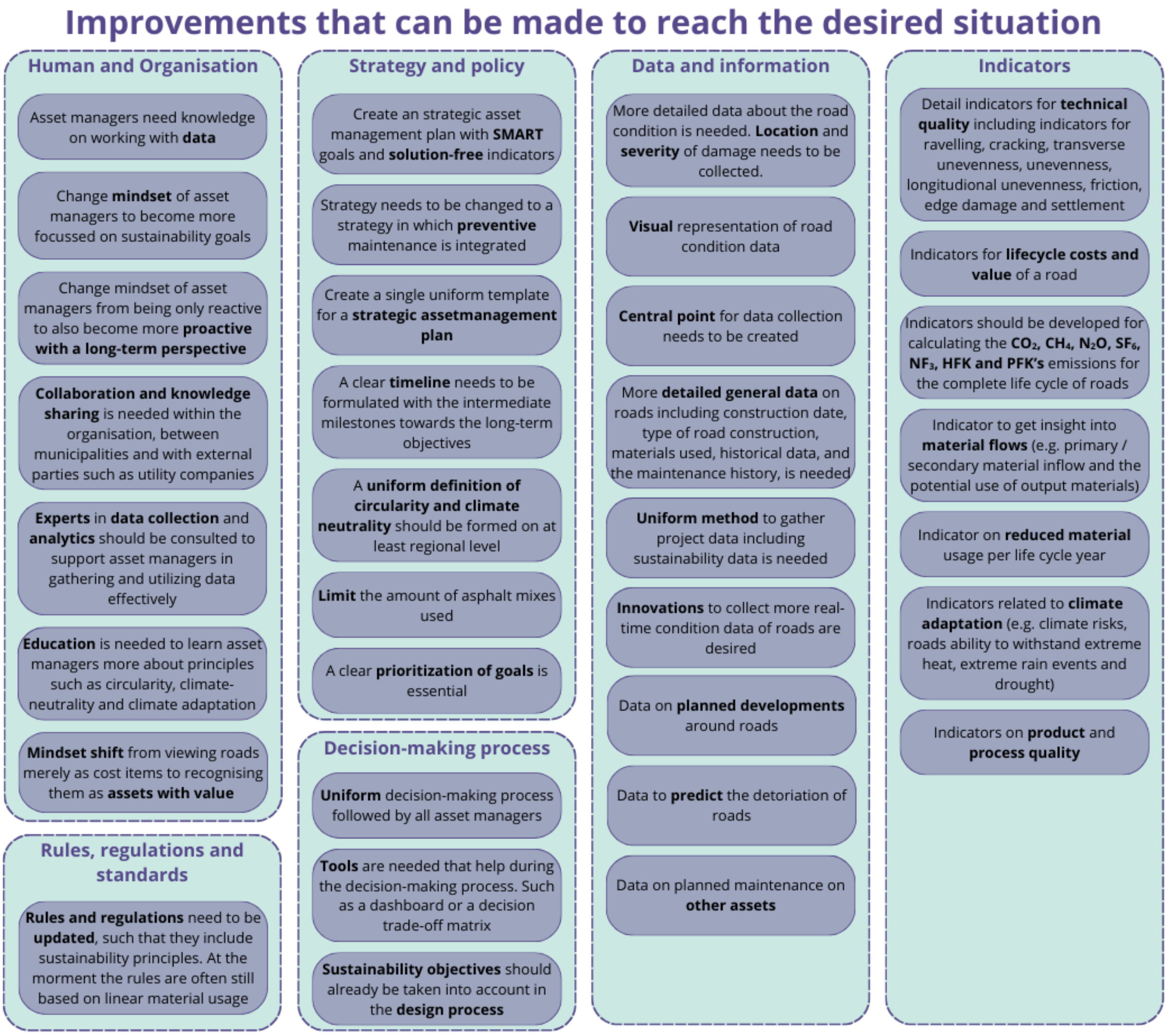


Figure 11 - Improvements needed to reach the desired situation

7.1 CHANGING THE ROLE OF ASSET MANAGERS OF THE FUTURE

Problems such as climate change complicate the decision-making process of asset managers, since it requires asset managers to take additional goals, such as the Sustainable Development Goals, into account in their decision-making process. It is observed that these goals are currently not always considered by asset managers, which hinders their achievement of these goals. To reach a situation in which all these goals are considered, the following steps can be taken:

1) A clear strategy and policy can be formulated
2) A shift in mindset can be made
3) Asset managers' data analysis skills can be improved

7.1.1 A clear strategy and policy

According to the workshop participants, the first step is to develop a **Strategic Asset Management Plan (SAMP)** that includes **SMART goals** and **clear indicators** to track progress. This is in line with what is written in the iAMPro model of the CROW as explained in Section 3.3.2 [55]. Currently, many asset managers have not formulated their goals in a SMART manner, which means they lack concrete, measurable targets. As a result, these goals are often not actively used in practice, making it difficult to effectively steer toward long-term objectives. This shortfall also hampers the achievement of broader ambitions, such as the **Sustainable Development Goals**. Therefore, it would be beneficial if asset managers start creating a SAMP with SMART goals and clear indicators.

In addition, the workshop participants emphasised the importance of including a **clear timeline** in the SAMP, outlining intermediate steps towards the final objectives. During the interviews, it appeared that asset managers currently do not have such a timeline. This need for a clear timeline with milestones is not explicitly mentioned in the explanation of the iAMPro model [55], but according to the workshop participants, there is a risk that long-term goals will not be achieved without such milestones. Therefore, it might be beneficial for asset managers to create such a timeline with clear milestones in their SAMP.

One of the workshop participants suggested that it would be helpful to develop a **single, uniform template for a SAMP** that municipalities can use as a foundation and adapt to their specific needs. A standardised SAMP template would enable municipalities to work more efficiently, as they would not need to start from scratch or figure everything out on their own. In the literature, such a standardised template for a SAMP could not be found. However, it might be beneficial for multiple municipalities to work together to create such a template.

Furthermore, the need for more **regular monitoring** was also mentioned during the workshop to assess the extent to which all objectives are being met. This corresponds with the iAMPro model of the CROW [55].

After creating a SAMP, it is essential to ensure that the plan remains up to date and that all objectives are effectively integrated in practice. Moreover, the associated indicators should, as far as possible, be **solution-neutral and measurable** to support objective evaluation and informed decision-making.

7.1.2 A shifting mindset is needed

Secondly, based on the interviews, it can be concluded that a shift in the mindset of asset managers is needed to reach the sustainability goals of the municipality. A shift is needed from an asset manager that is mainly focused on the technical quality of the road and costs towards an asset manager that is also focused on goals such as sustainability to be able to reach the Sustainable Development Goals. During the workshop, it was noted that a cultural shift is needed, one that **moves away from conservative thinking** and towards a more open environment where **knowledge** is actively **shared**.

To facilitate this shift in mindset, asset managers need more education and knowledge on sustainability terms such as “circularity”, “climate adaptation” and “climate neutrality”, since it became clear in the interviews that not all asset managers fully understood the definitions of these terms, which explains why these goals are not often implemented in practice. This finding was validated during the workshop. According to the literature, **education is also crucial to sharing knowledge and skills that are needed to create new institutions** [115].

Besides, to achieve these sustainability goals, a more proactive mindset is needed since, according to the literature, preventive maintenance can help in achieving the sustainability goals [109]. It might be beneficial for asset managers to change their mindset from being only focused on reactive maintenance to maintenance that is more **proactive**. To facilitate this shift, more data should be collected on, for instance, the expected deterioration of roads and the benefits that it offers to asset managers.

7.1.3 Asset managers' knowledge and skills regarding working with data

Moreover, to reach the desired situation in which decision-making is more and more based on data, asset managers need the skills and knowledge to work with data. According to the literature, education is needed to create new institutions such as more data-driven asset management [116].

7.2 Optimising the decision-making process

The current decision-making process is mainly based on the implicit knowledge of asset managers. A shift is needed to a more balanced decision-making process in which all the goals of asset managers need to be considered, and in which **preventive and reactive maintenance** strategies are considered. This change is necessary, as the sustainability goals are unlikely to be achieved without this change. To reach this situation, it can be helpful to formulate a **standardised and uniform decision-making process**, and tools need to be created, such as a **decision trade-off matrix or dashboard**. According to the interviews, it could be concluded that this would be useful for asset managers to make better informed decisions and to create insight into the results of their decisions.

Creating these tools and dashboards for the asset manager of the future requires the collection and analysis of more comprehensive data to enable accurate forecasting and measuring of the achievement of goals. Moreover, a change in the mindset of asset managers is necessary, moving away from reactive practices that only focus on technical quality, which represents goals related to safety, appearance, durability and comfort, towards a proactive, forward-looking strategy including sustainability goals. When this shift does not take place, the goals mentioned in policy documents will probably not be met.

Institutional change is required to introduce and embed new decision-support tools in asset managers' daily practice, such as dashboards, trade-off matrices, or indicator sets that can guide decision-making. To successfully implement this institutional change, it is essential that asset managers receive **education** [115] on policy objectives, particularly those related to sustainability, as well as on the practical use of tools designed to support decision-making to reach these objectives.

7.3 Indicators

A workshop was held to discuss the current indicators used to measure goals related to road quality, costs, climate neutrality, circularity, climate adaptation, and product and process quality. During this workshop, participants, comprising asset managers, contractors, university experts, and project managers from municipalities, were asked to identify the changes needed to achieve the desired situation, where most of these goals can be met and measured with indicators. This section discusses all the proposed changes to reach the envisioned outcome.

7.3.1 Technical indicators

During the workshop, several steps were discussed that need to be taken to gain better insight into the actual condition of roads and to ultimately move towards predictive maintenance. In the validation workshop, participants confirmed the finding of the interviews that the indicators of the visual inspections based on the CROW methodology can indeed sometimes give a distorted picture of road quality, as they assess road sections rather than specific damages.

It was emphasised during the workshop that the first step should be to **map out the existing road infrastructure** and assess its current quality. Additionally, the workshop participants and interviewees suggested that it would be better to **record specific damages with their location** and that, in the future, this should ideally be done automatically using, for example, camera footage analysed by artificial intelligence. To reach this situation, innovation is needed. In literature, it was found that in Sweden already efforts are made to combine new inspection methods with artificial intelligence, aiming to enable preventive maintenance, increase cost-efficiency, and minimise the environmental impact of road maintenance [114].

By accurately mapping road damage, it becomes easier to understand how roads deteriorate and to **predict their remaining service life**. To predict this effectively, indicators are also needed for factors that influence the lifespan of roads, according to the workshop participants.

7.3.2 Cost indicators

During the validation workshop, it was confirmed that asset managers should not only focus on the initial investment costs but also take into account the full life cycle costs of a road in the long term. This corresponds with what was found in the literature, where it was mentioned that by adopting a long-term perspective, high costs in the future can be avoided [94]. Participants emphasised the need for **a mindset shift from viewing roads merely as cost items to recognising them as assets with value**. To make this value visible and tangible, the use of appropriate indicators is essential.

For example, the Equivalent Uniform Annual Cost indicator (EUAC) can be used to evaluate the lifecycle costs of different maintenance strategies [75] (see Section 5.3.2.2.3). To support this, the author of this thesis developed a simple Excel tool to compare the EUAC of various strategies. Asset managers only need to provide inputs such as the expected maintenance costs, the timing of those costs, the interest rate, and the expected lifecycle duration of the road in years. By developing **simple tools** like this, it might become easier for asset managers to apply life cycle costing in their decision-making processes.

Additionally, it was noted during the workshop that sustainability should not automatically be seen as more expensive. Rather, it implies a different distribution of costs over time. Gaining insight into this shifting cost pattern requires **a broader perspective that goes beyond the initial investment and includes long-term financial impacts**. However, a key question raised during the workshop was: what is the actual lifespan of a road? According to participants, this is not a fixed number, it also depends on the choices and priorities of future generations.

7.3.3 Climate neutrality indicators

During the validation workshop, participants confirmed that emissions need to be measured more clearly to gain meaningful insights into progress toward climate neutrality. However, questions were raised about the **scope of these calculations**, for instance, whether additional fuel consumption should be included. While including such factors could improve the accuracy of assessments, it also adds complexity, and participants debated whether the added value would outweigh the additional effort.

The **need for a clearer definition of climate neutrality** was also emphasised. Several participants noted unclarity about existing goals, such as the 55% emissions reduction target. Specifically, it is unclear what the reference year is and which types of emissions are included in this calculation. To enable more effective monitoring and comparison, participants agreed that municipalities should adopt **consistent measurement methods and indicators**. This calls according to them for **collaboration, knowledge sharing and the establishment of standardised agreements** on how climate neutrality is defined and measured.

Another important topic of discussion during the workshop was the **relationship between climate neutrality and circularity**. While some participants felt these two goals may not always align, others argued that circularity can support progress toward climate neutrality. The consensus between the participants was that a clear **prioritisation** is needed between goals, and in this case, the workshop participants agreed that circularity should take precedence.

Furthermore, participants stressed the importance of considering the bigger picture. Climate neutrality indicators should be considered already in the road design phase, with a focus on the entire life cycle of the road. This approach requires a **long-term vision**, supported by indicators that can help justify decisions which may not yield short-term benefits but prove advantageous over time.

7.3.4 Circularity indicators

During the workshop, participants confirmed that the absence of clear definitions for circularity hinders both the implementation of fully circular practices and the development of meaningful indicators to measure circularity. The workshop participants agreed on the importance of establishing a **uniform definition of circularity** and proposed to do this on a **regional level**. The participants, all coming from the Twente Region, suggested that this definition should be developed **collaboratively** with the 14 Twentse municipalities and a selection of contractors. A regional approach was considered the most practical, as it can be realised more quickly than a national initiative. Once a clear definition is in place, appropriate indicators can be developed to measure circularity in greater detail. The indicators proposed by the platform CB'23, or for instance, indicators such as the material circularity index (see Section 5.3.3.2.3), can serve as inspiration for this.

Additionally, in a conversation with an expert in asset management, it was suggested that advancing circularity in infrastructure projects requires municipalities to collect more detailed data on the materials used in road construction. This aligns with literature created by, for instance, Platform CB'23, which has developed a guideline for creating material passports in the construction sector to promote circular practices [112]. This calls for changes in the current data collection practices of asset managers. To support this, (regional) collaboration could be initiated to develop **a standardised method for collecting data** that supports both circular practices and the monitoring of circularity levels across municipalities.

The workshop discussions also showed the need to integrate circularity more thoroughly into the road design phase. Participants agreed that **circularity should play a central role early in the design process**. This requires a shift in current working methods, with circularity becoming a standard component of design considerations. Standard indicators and data should be developed to assess the circularity of designs effectively.

Finally, participants noted that existing **calculation rules and regulations** often act as barriers to the use of circular materials, as they are focused on primary material usage. To overcome this challenge, it was suggested that these rules need to be revised to better accommodate and encourage the use of circular alternatives.

7.3.5 Climate adaptation indicators

Moreover, the validation workshop showed the importance of **gaining insight into the specific climate adaptation needs of different locations**. These needs should inform a tailored approach in the road design process, where **climate adaptation becomes an integral component**. While making roads more climate-adaptive can bring clear benefits, such as preventing issues related to climate change, participants also noted potential drawbacks, particularly concerning the roads construction.

According to the workshop participants, a **shift in mindset** is needed: one that embraces a long-term and flexible perspective. A key question raised during the discussion was how far into the future municipalities should plan, and to what extent certain climate-related damages can or should be accepted. One participant referred to this as the concept of "climate acceptance," which shows the need for municipalities to **define indicators with their thresholds and boundaries** in the face of inevitable climate impacts.

7.3.6 Product and process quality indicators

The validation workshop revealed that data on both product and process quality is indeed necessary to improve the asset management practices. However, it became clear during the workshop that much of this data and indicators only become available after the construction process has been completed (e.g. temperature homogeneity and number of roller passes per location). A contractor present at the workshop emphasised the importance of also having **information and indicators about process quality during the construction phase**, so that adjustments can be made in real time. Currently, they do not often have this data on the construction site. Therefore, innovations need to be done in the future so that more real-time construction data can be collected and real-time indicators are available that give insight into the process quality. Literature shows that efforts are already being made to collect real-time data, and that this indeed enables operators to make more informed decisions during asphalt construction, thereby improving both the process and the quality of the final product [113].

It was also mentioned during the workshop that **temperature has a significant impact on asphalt quality**. Currently, so many different asphalt mixtures are used that the asphalt plant needs to be restarted for each type. As a result, it can happen that the asphalt needed for a specific location later in the day is already produced in the morning, potentially compromising its quality.

To improve process quality, the workshop participants stressed the importance of **reducing the variety of asphalt mixtures**, so that the asphalt plant does not need to be restarted as frequently. Achieving this will require greater collaboration between municipalities, which calls for a **cultural shift and more knowledge sharing,** according to the workshop participants. A point of discussion during the workshop was who should take the lead in initiating this cooperation. Some participants expressed concerns that using a limited amount of asphalt mixes could hinder innovation, but the general opinion was that it does not have to hinder innovation. In fact, innovations can replace older "standard" mixtures, which allows for improvement.

7.4 MONITORING AND DATA COLLECTION IN THE FUTURE

To determine whether the goals outlined in policy documents are being achieved, roads must be monitored and data must be collected. Additionally, data collection is essential for making more strategic decisions. Involving **experts in data collection and analytics** might help optimise the use of data, enabling asset managers to make better, well-informed decisions in the future.

These experts in data collection and data analytics can help in improving data collection and data analysis related to:

1) General information
2) Condition data, and
3) Sustainability and project data

7.4.1 General information

Based on the interviews, it could be concluded that to support strategic decision-making, it is also essential to **centralise and collect general road data**. This includes information such as the construction date, type of road construction, materials used, historical data, and the maintenance history. Having this information readily available in one place ensures a more integrated and informed decision-making process.

From the interviews, it could be concluded that once the foundational data is in place, it must be **regularly updated**. For example, when a road is maintained or replaced, the corresponding project data should be added to the road's general information. During the interviews, it was mentioned that this is currently not always done.

Additionally, according to the interviewees, data on planned maintenance for other assets and upcoming developments in the surrounding area are essential for better planning of road maintenance. Therefore, it would be beneficial for different departments within a municipality to store their data in a **standardised manner**, making it exchangeable. For instance, this would allow all planned activities in an area to be visualised on a single central map. This requires **collaboration** not only between departments within the municipality but also with external stakeholders, such as utility companies.

The workshop participants agreed that to prevent capital loss, it is indeed essential to have access to information on planned maintenance on other assets and developments in the area, and that achieving this demands collaboration. Some participants noted that there are already initiatives underway to centralise this data, but a key challenge remains: keeping the information up to date.

7.4.2 Condition data

To improve monitoring and data collection of road conditions, it is essential, according to the interviewees, to **more accurately record both the location and severity of damage**. Insights from the interviews and validation workshop indicate that this would significantly enhance asset managers' understanding of road deterioration over time. Additionally, it would be beneficial in the future to **visualise** the condition data of roads on a map, as many asset managers indicated that this helps them make more strategic decisions and gain a clearer overview of the current road conditions. It was mentioned by some of the interviewees that there are already methods to do this, however, these are hardly used, and these methods are expensive. Therefore, changes are needed to reduce the costs of visualising this data on a map, such that the conditions of roads are visualised more structurally on a map, which can help asset managers to get a better insight into the condition of their roads.

Emerging **technologies** can also be tested and employed in the future to assess road conditions and support more strategic decision-making. Technologies such as drones, sensor-equipped vehicles, and other advanced measurement tools might provide more objective and detailed data on road conditions in the future. This data can subsequently be used to get better insight into the deterioration of roads.

7.4.3 Project data and sustainability data

A **clear plan is needed for project-related data collection to measure if the strategic goals of asset managers are reached**. For example, if sustainability is a key objective, it is important to define what data should be collected to monitor progress in this area. This requires asset managers to first reflect on which specific goals they aim to achieve and then align their data collection accordingly.

From the interviews, it became clear that establishing a **standard data collection template** for projects can be beneficial, as it allows municipalities to compare projects and monitor the achievement of their goals. These templates could be developed collaboratively among different municipalities to avoid duplicating efforts. This standard data collection template should include, among other things, data collection related to circularity, climate adaptation, and climate neutrality as discussed in Section 6.4.3. This data can, for instance, include the expected prolonged life span of the road, the materials used in a project and the greenhouse emissions during a project.

8 DISCUSSION

This chapter discusses the implications of this research for asset managers and how these results can help them improve their decision-making process (see Section 8.1). Furthermore, this chapter discusses the implications of this research for the organisation (see Sections 8.2 and 8.3). The qualitative research methods used in this research have some shortcomings that influence the results of this study. Therefore, the limitations of this research are also discussed in this chapter (see Section 8.4). Lastly, there is a reflection on the literature findings versus the findings of the interviews and the workshop in Section 8.5.

8.1 IMPLICATIONS FOR ASSET MANAGERS

This research has identified data, indicators and changes needed to support more strategic decision-making in the field of asset management of municipal roads. Besides, a possible direction is created to support asset managers in improving their working practices. Asset managers and initiatives such as the Wegverleggers can use these insights to reflect on their current working practices and to identify opportunities for improvement in their working methods. These improvements can help them to better reach their goals in the future.

Besides, it is important to note that the decision-making process of asset management presents a "wicked problem," meaning there is no singular solution representing the most optimal desired future situation and the most optimal decision-making process for asset managers. The changes proposed in this study represent just one possible route to reach a desired situation, developed based on interview findings, the validation workshop, and the author's interpretation of these interview and workshop results. Asset managers can also take other routes to their desired situation, but the findings of this thesis can serve as inspiration for them.

The same applies to the indicators to measure whether asset managers are achieving their goals. Chapter 5 outlines multiple indicators that asset managers can use to measure if their goals are reached. However, asset managers should decide for themselves which indicators they are going to use in practice, which is dependent on the priorities of each asset manager. This research serves as a guide to help asset managers select the most appropriate indicators for measuring their specific objectives

Moreover, asset managers have to decide for themselves what their desired situation is and how they want to reach this situation, and this is influenced by multiple factors, such as political factors. From this research, it became clear that many asset managers need to rethink their working practices if they want to achieve, for instance, the sustainability goals. It is observed during this research that asset managers often have insufficient workforce capacity to rethink and change their working practices. Therefore, to do this efficiently, collaboration between asset managers of different municipalities would be beneficial since it would reduce the workforce capacity needed. By collaborating, municipalities do not have to individually figure out how to improve their asset management practices; they can learn from one another, leading to more effective ways of working.

This research also shows the growing importance of data-driven decision-making and its potential to support a more strategic approach to managing roads. The research provides asset managers with insights into the data that they currently possess and what additional data could be collected in the future to enhance their decision-making processes. However, the pathway to a situation where data plays a central role is not yet established in many municipalities. While some individual municipalities are exploring ways to collect more data, a broader, coordinated approach is still lacking. Sharing knowledge and experiences regarding new data collection methods could be highly beneficial, enabling municipalities to learn from one another and accelerate progress.

8.2 Implications for the Organisation

Implementing the proposed changes outlined in Chapter 7 requires organisational adjustments and a clear awareness of the need to adapt current working practices. Therefore, it is essential to explore, in future research, how organisational practices must evolve to support more effective strategic decision-making by asset managers. During the validation workshop, participants repeatedly emphasised the necessity of organisational adjustments to achieve the full range of municipal goals related to road asset management.

Achieving the Sustainable Development Goals requires a transition within municipal organisations, from a traditional working culture focused on technical quality, control, and cost-efficiency, to an approach that integrates sustainability, encourages collaboration between market actors and governmental organisations, and recognises assets as valuable societal resources. In addition, shifting from a working process largely based on implicit knowledge to one in which decisions are based on data can support more balanced, goal-oriented decision-making. Moving towards this value-oriented and data-driven system requires a fundamental change in the working practices of municipalities. What this transition looks like, and the roles that municipalities and market parties play in it, depend on the specific context and the choices made by municipalities. Given the extensive knowledge held by market parties, collaborating with them could be useful for municipalities to achieve their goals, since at the moment, not every municipality has enough employees with the needed competencies to achieve the transition on their own.

To enable this transition, municipalities must fundamentally rethink their organisational practices. They need to take a proactive role in guiding the transition, ensuring that responsibilities are clearly defined and that market actors can anticipate and align with the evolving transition pathway. Closer cooperation between municipalities could facilitate this process more efficiently. By collectively pursuing a shared direction, municipalities can create uniformity, which not only strengthens their own transition efforts but also provides greater clarity and predictability for market participants.

Governmental organisations can also collaborate with market parties to develop new technologies and tools that support the achievement of municipal goals. These collaborations can be either short-term or long-term. Long-term collaborations provide greater certainty for market parties than short-term collaborations, as they increase the likelihood that innovations can be reused across multiple projects. This, in turn, improves the chances for market parties of recovering the investments made in developing these innovations. In this way, long-term cooperation helps to stimulate private sector investment by providing continuity and predictability.

However, questions can arise around the ownership of these innovations when new technologies or tools are developed jointly with, for example, market parties. On the one hand, governmental organisations want to encourage market parties to invest in innovations. On the other hand, when these innovations are facilitated through collaboration, it remains unclear who owns the resulting outcomes, the governmental parties or the market parties. To prevent conflicts, municipalities need to develop a clear vision and policy on how to manage ownership of jointly developed innovations.

8.3 TRANSITIONAL CHALLENGES

The transition needed within organisations, as discussed in Section 8.2, also comes with several challenges. For example, transitioning towards more data-driven asset management requires internal expertise within municipalities to manage and utilise data effectively. This requires investment in training staff to work effectively with such data. Transforming the working methods of asset managers demands time, financial resources, and effort. Given their already high workload, this can be a significant barrier to change. However, in the long term, these changes have the potential to reduce both costs and workload related to asset management. Moreover, investments are needed to educate asset managers on topics such as sustainability goals. This knowledge is essential to ensure that these goals of municipalities are effectively translated into practice.

During the workshop, it was also noted that increased collaboration, at least on a regional scale, is needed to, for example, develop a clear and uniform definition of circularity. Furthermore, workshop participants suggested that it could be beneficial for municipalities to, for instance, jointly create a standardised template for a SAMP. Municipalities could also work together to move towards more data-driven asset management. However, it remains unclear who should take the lead in initiating such collaborations and how these collaborations should be organised. Front-runners are needed to set up such collaborations. Initiatives like the “Wegverleggers,”[6] led by the municipalities of Enschede and Losser, along with NTP and Roelofs, could serve as a starting point for municipalities to work together on, for instance, developing a standardised SAMP template. However, the current focus of the Wegverleggers is on knowledge sharing, this should be expanded to include joint development efforts, such as co-creating tools, guidelines, or templates to facilitate this.

Establishing these collaborations can be a time-consuming process, which can be a barrier to initiating these collaborations, especially as many organisations are already dealing with high workloads. Successful collaboration requires a lead organisation to take initiative and coordinate this collaboration. Currently, multiple of the interviewed municipalities show a desire to collaborate more intensively, but structural, long-term collaborations are often not established due to a limited workforce capacity. Nevertheless, once a collaboration is well established, the workload per organisation can decrease over time, as responsibilities and tasks can be shared across the participating organisations. Achieving this, however, requires trust between the different parties. To establish this trust and support effective collaboration, it may be necessary to organise trust-building activities and workshops on collaboration. The need for such efforts depends on how familiar the organisations already are with collaborative working methods.

8.4 LIMITATIONS OF THE RESEARCH

First of all, the qualitative nature of this research poses some limitations. In this research, a relatively small number of asset managers were interviewed, due to the time-intensive nature of conducting and analysing interviews. Given the relatively small number of interviews, it might be that not all missing data and indicators are identified. Based on the conducted interviews, conclusions are drawn. However, it might be that other asset managers in the Netherlands have a different decision-making process and encounter other problems. Therefore, the generalizability of the results is limited.

Additionally, the specific location or context in which asset managers operate may influence their responses during the interviews, thereby also limiting the generalizability of the findings. During the interviews, it was for instance seen that asset managers of large cities have different problems

[6] Link to the website of the Wegverleggers: Innovatief en duurzaam asfaltonderhoud | Wegverleggers

than asset managers of large villages. Furthermore, both the responses provided by the interviewees and the interpretation of the interviews of these responses involve subjectivity. Therefore, it might be that when the research is conducted by someone else, the conclusions can slightly deviate from the findings in this research.

Furthermore, the desired situation sketched in the research is based on the findings of the interviews and the workshop. The desired situation is dependent on many factors and is also dependent on personal preferences. Therefore, there might be slight differences between individual opinions on the desired future situation. While sketching the future desired situation in this research, as many opinions of asset managers as possible are considered, next to what is written in policy documents.

Moreover, multiple asset managers were invited to participate in the validation workshop. Three of these asset managers cancelled shortly beforehand, resulting in a limited number of asset managers that joined the workshop. Consequently, the conditions for validating the research findings were not optimal. It is likely that the presence of more asset managers would have contributed to a more robust and accurate validation process. However, the group of workshop participants was quite diverse, which resulted in interesting discussions.

Besides, to reach the future desired situation, innovations are needed. The innovations that need to be done in the future to reach the desired situation can be steered by asset managers. However, which innovations will be done in the future and how they will work out are still uncertain. Moreover, it is uncertain which other challenges asset managers have to deal with in the future, which can possibly influence the most suitable method for improving the decision-making process.

Another limitation of this research is that the focus of this thesis is specifically on asphalt pavements. While asphalt is currently the dominant material used for road surfaces, its future suitability, particularly from a sustainability perspective, is uncertain. To meet long-term environmental goals, a shift toward alternative pavement materials might be necessary. Although efforts are made to examine indicators that are as solution-neutral as possible, their applicability to other materials still requires further investigation. Given the current "lock-in" to asphalt, such transitions to other materials are unlikely in the short term, while it might be beneficial to consider alternative pavement materials in future strategies.

Moreover, only indicators and data for a few goals of asset managers are considered during this research, given the time available for the research. Goals such as biodiversity are not taken into account in this research since asset managers of roads have a limited impact on these types of goals. The work of asset managers is influenced by many interconnected aspects that make the decision-making process of asset managers quite complex. Therefore, it might be that certain aspects are overlooked in this research.

Lastly, this research primarily focuses on the management phase of the asphalt road life cycle, examining the data that can be collected and the improvements that can be made during this phase to help asset managers achieve their goals. However, achieving broader sustainability goals also requires attention to other phases of the life cycle, which asset managers can influence to a lesser extent. In addition, data on other assets that impact asphalt roads should be taken into account. While this thesis does not explicitly address these aspects, they are essential for meeting the full range of municipal objectives. Therefore, it is recommended that future research explore both the interconnections between different assets and the entire life cycle of roads.

8.5 REFLECTION ON LITERATURE VERSUS THE RESEARCH FINDINGS

It can be concluded that findings from the literature and those from practice do not always align. First, there is a relatively small amount of academic literature concerning the asset managers of roads in the Netherlands. During the interviews, the asset managers were also asked which literature they used, but almost none of them used literature. The primary and only document frequently referenced by asset managers is the CROW guideline [62], which is intended to support the decision-making processes of asset managers of roads. However, it appears that not all asset managers actively apply the outcomes of the CROW process in practice. A factor that causes this is that the indicators provided in the CROW guideline focus mainly on road sections and, according to several asset managers, fail to offer a sufficiently detailed overview.

Moreover, the literature emphasises the importance of considering sustainability goals as an asset manager, providing a range of indicators to support these goals [14] [39] [40] [34] [10] [37] [35] [88] [91]. Nevertheless, these goals and indicators are often not implemented in practice. To bridge the gap between literature and practice, it is necessary to establish clear targets within strategic asset management plans, encourage a mindset shift among asset managers, and enhance asset managers' knowledge of relatively new objectives, such as sustainability targets.

9 RECOMMENDATIONS

In this section, multiple recommendations are given to asset managers about methods that can help them make more strategic decisions that enable them to more effectively reach their goals. Besides, recommendations for future research are given that need to be conducted to improve the decision-making process of asset managers.

9.1 CHANGE THE MINDSETS OF ASSET MANAGERS

The first recommendation is that the mindsets of asset managers need to be changed from being mainly focused on “traditional” goals such as safety, accessibility and costs to also take into consideration additional objectives mentioned in policy documents related to sustainability, otherwise, these goals will probably not be reached.

It is advised to reach this mindset change by, for instance, giving more education on the sustainability goals and on methods to reach these goals. Moreover, asset managers are advised to collaboratively formulate a clear vision of the desired future situation, ensuring they have a shared understanding of the goal they aim to achieve.

9.2 DEFINE SMART GOALS AND INDICATORS

Furthermore, it is advised to formulate the goals of asset managers in a strategic asset management plan according to the SMART criteria and to formulate indicators to measure whether the objectives are reached. While many policy documents include clearly defined targets for road quality, this is often not the case for sustainability-related goals. These objectives are frequently not formulated in a specific, measurable, or time-bound manner. Moreover, there is a lack of clear indicators to monitor progress toward these goals, which appears to hinder their effective implementation. Therefore, it is advised to formulate SMART objectives alongside appropriate indicators.

Moreover, it is recommended to develop a uniform template for a strategic asset management plan that municipalities can adapt to their specific needs. Having such a standardised template could help municipalities work more efficiently when preparing their strategic asset management plans. It is advised to set up a working group with different municipalities to create such a template.

9.3 SET UP A DATA COLLECTION PLAN AND VISUALISE DATA

It is recommended that asset managers develop a road passport to systematically track essential information about each road. Moreover, to effectively measure the achievement of goals, it is essential to develop clear plans for data collection. First and foremost, it is recommended that asset managers from different municipalities collaborate to create a shared data collection plan for sustainability indicators. Contractors should also be involved in this process, as they are often responsible for collecting the majority of sustainability-related data. Asset managers can include specific data collection requirements in the tender phase to ensure this information is gathered. It is further advised that all municipalities collect the same types of data to ensure comparability and to enable a more advanced and uniform data collection process.

In addition, systematic plans must be developed for the collection of road condition data. Several municipalities are already investigating new methods to gain more detailed insights into the condition of their road networks. It is recommended that municipalities work together more closely in exploring and evaluating these new approaches. Interviews revealed that many municipalities are currently working independently to find the most effective methods, whereas a collaborative effort would likely result in greater efficiency and shared learning.

Once this condition data is collected, it is recommended to visualise this data in an interactive map that displays the road status in (near) real-time. This can help asset managers to get better insight into the condition of their roads. Achieving this (near) real-time insight into the condition of the roads requires more frequent data collection. It is also advisable to collect data at regular intervals in a consistent manner to gain better insights into how damage develops over time.

Finally, asset managers are encouraged to gain better insight into the initial quality of roads, as this can significantly improve the ability to predict future maintenance needs. It is advisable to collect data on both product quality and process quality during road construction, as this information can help identify potential risk areas. To achieve this, asset managers should actively collaborate with contractors to gather data on the initial road quality at the time of construction. This data can serve as a valuable input for predicting long-term asset performance and estimating future maintenance requirements.

9.4 CREATE A DASHBOARD

It is recommended to create a dashboard for asset managers as a practical tool to enable them to make more strategic decisions. During the interviews, asset managers confirmed that a dashboard can be a useful tool for them. A dashboard is a visual tool for organising and interacting with data. It helps users explore dataset characteristics and structures, and interpret trends, all without requiring specialised analytics skills [117]. However, a dashboard is only useful if the data and information used as input are of high quality and can be accessed in a timely manner [118]. According to the literature, the data platform used to make the dashboard needs to be highly flexible in the technologies it can interface with to remain current and it can grow with expanding needs. The data platform needs to be designed with modularity so that sections of the data platform can be updated independently [118]. For a dashboard intended for asset managers, it is recommended to implement it in a GIS environment, allowing data to be visualised on a map. Programs such as Excel can also be used, but a limitation of Excel is that data cannot be visualised in an interactive map.

In this dashboard for asset managers, indicators such as those mentioned in the result section of this report should be incorporated to make a well-balanced decision based on all the goals that a municipality has. It is recommended to include building blocks related to circularity, climate neutrality, climate adaptation, technical quality, costs and product and process quality in the dashboard. Based on the interviews, it can be concluded that such a dashboard should be highly visual, including maps that visualise the status of roads. This dashboard should provide asset managers with clear, real-time insights into their current performance relative to strategic goals. Furthermore, the dashboard should allow for the comparison of alternative strategies, facilitating the selection of the option that best supports the achievement of those goals.

Furthermore, the interviews revealed that the building blocks for an effective dashboard should provide insights into several aspects of asset management (see Appendix D for a conceptual version of a possible dashboard, including most of these aspects, made by the author of this thesis as a source of inspiration). These include:

- General information on the assets, such as maintenance history, year of construction, location, etc.;
- The materials used across all assets;
- The technical quality of the roads;
- Safety;
- Accessibility;
- Sustainability aspects such as circularity, climate adaptation and climate neutrality;
- Budget and the lifecycle costs;

- An overview of road damages and their specific locations;
- The progression of damages over time and the expected remaining life of an asset;
- The ability to link reported damages to inspection data;
- The identification of opportunities for alignment with other projects in the area;
- Predictive insights into how the road network's quality would evolve under different maintenance strategies; and
- A clear indication of whether overall road quality is improving or deteriorating.

According to the literature [119], creating a dashboard involves several steps: (1) planning, (2), gathering requirements, (3) designing, (4) constructing and testing, (5) deploying, and (6) maintaining [119]. Asset managers can already start with step 1 up to and including step 4. It is advised that municipalities work together in creating such a dashboard. To deploy the dashboard, first, data is needed. Currently, not all data is available yet. Therefore, it is recommended to develop a strategy for collecting the required data to create a dashboard that can help in making improved strategic decisions.

9.5 IMPROVE THE DECISION-MAKING PROCESS

Asset managers are advised to reconsider their decision-making processes based on the findings of this research. It is recommended that they develop tools, such as a decision trade-off matrix or a strategic dashboard, to support more informed and strategic decision-making. These tools should take into account all relevant municipal goals to ensure a well-balanced approach.

In addition, the decision-making process can be further improved by developing a standardised decision tree to be used consistently across all projects. This would contribute to a more systematic and structured approach to asset management. Furthermore, a shift is needed from primarily reactive methods towards approaches that also incorporate preventive maintenance. As such, preventive maintenance options should be integrated into the decision tree to support long-term asset sustainability.

9.6 ASSET MANAGERS WORK TOGETHER TO REACH YOUR GOALS

Furthermore, it is advised to asset managers to collaborate more closely with asset managers of other municipalities. After all, all municipalities have similar goals and challenges they need to overcome to reach the best management strategy for their roads. Collaboration can help to learn from each other and to establish the most optimal working method.

Currently, it has been observed that most municipalities are working independently to improve their decision-making processes. One interviewee expressed a desire for greater collaboration but noted the absence of a structured approach to do so. Therefore, it is recommended to establish more structural collaborations between municipalities to facilitate knowledge sharing and joint development of best practices. Initiatives such as the Wegverleggers could be the starting point for setting up these more structural collaborations between municipalities so that municipalities can learn from each other.

9.7 FUTURE RESEARCH

For future research, it is advised to also conduct interviews with experts in the field of data collection and modelling to create a better insight into what opportunities are available for using data to make better strategic decisions. Besides, it is recommended to do more research on (cheaper) data collection methods and real-time data collection.

Lastly, it is recommended to conduct further research to identify the factors that influence road deterioration and to develop predictive models for road deterioration based on these factors.

10 CONCLUSION

The research was conducted to answer the following question: "*What indicators, data and changes are necessary to assess whether the goals of the asset managers of the future are being met, and to support more strategic decision-making?.* To get a better insight into which data, indicators and changes are needed in the future to help asset managers to make better strategic decisions. Therefore, in this conclusion, answers are given to the four sub-questions that combined form the answer to the main question.

Sub-question 1: What are the client/asset manager's goals in general and concerning 2030 -2050?

The primary objective of asset managers is to maintain the assets in public space as strategically as possible throughout their lifecycle, minimising capital destruction while maximising their societal value. Although the goals of asset managers vary from municipality to municipality, almost all of them strive to find the right balance between cost, performance and risk. The main focus of asset managers is to ensure road safety by maintaining roads above a certain quality level. Additionally, asset managers aim to make the roads accessible for everyone, and they want to ensure that the visual quality of their assets is acceptable.

Sustainability-related goals, which are relatively new to asset managers, impact the asset managers' working methods. Both international and national policies require asset managers to reduce their greenhouse gas emissions, to become as circular as possible and to become climate resilient. However, these goals are not always considered in practice by asset managers. Achieving these sustainability goals requires innovations that can contribute to these goals while maintaining or even increasing the quality and lifespan of the road. To enable these innovations, the working methods of asset managers need to change and require increased collaboration among different parties. Besides, a clear SAMP with SMART goals, indicators and intermediate milestones is needed to close the gap between the goals written in the policies of municipalities and the goals considered in practice.

Sub-question 2: How do asset managers currently make decisions and integrate policy goals, data, and indicators into their daily practice?

The interviews revealed that asset managers currently follow a reactive approach to road maintenance. This means that maintenance is typically carried out only after damage has occurred, with little effort made to prevent such damage in advance. Most asset managers rely on the CROW visual inspection guidelines (publications 146 & 147) to assess the condition of roads and to determine necessary maintenance.

These inspections primarily provide insight into the technical condition of roads, supporting objectives such as safety, appearance, and comfort. However, sustainability-related goals are still relatively new for asset managers and are not yet structurally embedded in their decision-making processes. When sustainability is considered, it is often done on an ad hoc basis, and there are no clear indicators to measure the extent to which these goals are achieved.

Currently, asset managers collect general road information, such as the construction date, along with road condition data based on the CROW guidelines. Several interviewees indicated that this condition data is not always sufficiently detailed or objective enough. They expressed a need for more precise data on road conditions to improve maintenance strategies. As a result, some municipalities are experimenting with new inspection techniques. Nonetheless, there appears to be little collaboration between municipalities in testing these methods.

Moreover, data related to sustainability goals is rarely collected in a standardised way by asset managers. The research showed a clear need for more structured and comprehensive sustainability data to support the achievement of the sustainability goals.

Sub-question 3: Which indicators and data are considered relevant according to the literature and asset managers for making more optimal asset management decisions and determining whether the objectives of the client/asset manager are being achieved?

The interviews revealed that asset managers have different opinions on the data and indicators required to measure their objectives. However, it can be stated that all asset managers currently use the indicators from CROW's global visual inspection to assess the technical quality of their roads. These indicators provide insights into the severity and extent of road damage, such as ravelling, transverse unevenness, general unevenness, edge damage, cracking, and settlement, serving as indicators for safety, aesthetics, durability, and comfort. Nevertheless, several asset managers noted that these indicators lack sufficient detail and are partly subjective. Consequently, some asset managers want to use additional measurements and alternative inspection methods to obtain a more detailed and objective assessment of the road condition.

According to the literature, more detailed indicators such as rut depth and the International Roughness Index (IRI) can be used to get an insight into road conditions. However, the costs associated with the measurements for these indicators must be justified by their benefits. Currently, many municipalities are experimenting with new inspection techniques to acquire more detailed and objective data. By collecting this data, they aim to gain a better understanding of road behaviour, enabling more proactive and preventive maintenance strategies.

Additionally, multiple asset managers indicated during the interviews that they seek to improve their estimations of the remaining road lifespan to facilitate more informed decision-making. This requires data on parameters influencing road durability. Moreover, more real-time data is needed on the condition of roads to better predict the deterioration of roads. Falling weight deflectometer measurements can also be used to estimate the remaining lifespan of roads, but their high costs limit their application on a large scale.

Moreover, asset managers require data to prioritise road maintenance when there is a limited budget. This prioritisation should take into account factors such as traffic intensity, types of road users, and the surrounding environment. Therefore, information on all these factors needs to be collected.

Finally, data and indicators are needed to evaluate whether sustainability objectives are being achieved. At the moment, asset managers are missing comprehensive data to assess the achievement of, for instance, the Sustainable Development Goals and have not yet established concrete indicators. To create concrete indicators, first, clear definitions of the sustainability goals need to be established. Subsequently, indicators need to be defined that directly measure the achievements of the goals. According to the literature, several indicators can be used to measure municipal sustainability objectives, such as the CB'23 indicators and the MCI. To effectively measure these kinds of indicators, it is important that the appropriate data is collected within each project through collaboration between contractors and clients.

Sub-question 4: Which changes to current asset management practices can support more strategic decision-making by future asset managers?

To enable a more strategic decision-making process in asset management, several changes can be made. These changes include the following key areas:

- **Knowledge sharing and education**: Asset managers require enhanced knowledge in the fields of data analysis and sustainability principles to integrate sustainability goals more systematically into their decision-making processes. Furthermore, recognising the value of knowledge sharing, both within organisations and between municipalities, contractors, and external stakeholders such as utility companies, is essential. Facilitating structured knowledge exchange can significantly improve the quality of decision-making in asset management efficiently.
- **Mindset shift:** A shift in mindset is also crucial. Asset managers need to transition from a predominantly technical reactive approach to a more proactive one, including sustainability principles, with a stronger focus on the long-term implications of their decisions. In addition, there must be a fundamental change in how roads are perceived: rather than viewing them solely as cost drivers, they should be seen as assets with value that contribute to broader municipal goals.
- **Collaboration:** Effective collaboration between municipalities, contractors, and other external parties is crucial for achieving the wide range of goals that asset managers are tasked with in an efficient manner. The research shows the need for joint efforts in developing clear definitions of municipal objectives and improving the efficiency of municipal operations. During the validation workshop, participants emphasised the potential benefits of introducing a standardised SAMP template to increase efficiency. Moreover, stronger inter-municipal agreements are needed to reduce the variety of asphalt mixes in use, thereby improving asphalt quality.
- **Strategic asset management plan:** A clear Strategic Asset Management Plan (SAMP) with SMART goals, well-defined indicators, and milestones appears to be essential for asset managers of roads to enhance their strategic decision-making process. Many asset managers currently lack such a SAMP, despite the interviews and literature showing that it can significantly support more strategic decision-making.

In conclusion, multiple institutional and practical changes can be made to support the transition toward a more strategic, future-oriented approach to asset management. These include enhancing knowledge, adopting a proactive mindset, creating a clear SAMP and strengthening collaboration across stakeholders.

11 REFERENCE LIST

[1] Centraal Bureau voor de Statistiek, “Hoeveel reisden inwoners van Nederland en hoe?,” CBS, [Online]. Available: https://www.cbs.nl/nl-nl/visualisaties/verkeer-en-vervoer/personen/hoeveel-reisden-inwoners-van-nederland-en-hoe-. [Accessed 13 February 2025].

[2] TNO, “Asfalt in Nederland,” [Online]. Available: https://www.tno.nl/nl/duurzaam/infrastructuur/asfalt/. [Accessed 3 February 2025].

[3] Rijkswaterstaat Ministerie van Infrastructuur en Waterstaat, „Roadmap transitiepad Wegverharding,” NewForesight, 2022.

[4] Overheid.nl Wettenbank, “Wegenwet,” 1 January 2024. [Online]. Available: https://wetten.overheid.nl/BWBR0001948/2024-01-01#HoofdstukIV_Artikel17. [Accessed 19 February 2025].

[5] A. Mohammadi and L. A. Jimenez, Asset Management Decision-Making for Infrastructure System, Springer, 2022.

[6] Centraal Bureau voor de Statistiek, “Hoe belangrijk is vervoer over land voor de Nederlandse economie,” CBS, [Online]. Available: https://www.cbs.nl/nl-nl/visualisaties/verkeer-en-vervoer/economie/vervoer-over-land. [Accessed 13 February 2025].

[7] E. G. Too, „A Framework for Strategic Infrastructure Asset Management,” in *Definitions, Concepts and Scope of Engineering Asset Management*, Springer, 2010, pp. 31-62.

[8] L. Volker, A. Ligtvoet, M. van den Boomen, P. Wessels, T. van der Lei and P. Herder, “Asset management maturity in public infrastructure: the case of Rijkswaterstaat,” *International Journal of Strategic Engineering Asset Management,* pp. 439-453, 2013.

[9] Gemeente Enschede en Losser, „Meerjarige programmatische aanpak Groot Onderhoud Asfaltwegen gemeente Enschede en gemeente Losser versie 0.3,” 2023.

[10] Rijksoverheid ministerie van Infrastructuur en Milieu en het ministerie van Economische zaken, “Nederland circulair in 2050,” 2016.

[11] E. Keijzer, G. Leegwater, V.-E. S.E. and M. de Wit, “Carbon footprint comparison of innovative techniques in the construction and maintenance of road infrastructure in The Netherlands,” Elsevier, 2015.

[12] L. van Hoogevest and P. Derks, Wegbeheer 2011, Ede: CROW, 2011.

[13] H. Rittel and M. Webber, “Dilemmas in a General Theory of Planning,” *Policy Sciences,* vol. 4, no. 2, pp. 155-169, 1973.

[14] United Nations, “The 17 goals,” [Online]. Available: https://sdgs.un.org/goals. [Accessed 11 February 2025].

[15] Ministerie van Infrastructuur en Milieu, „Nationale klimaatadaptatiestrategie 2016 (NAS)," Ministerie van Infrastructuur en Milieu, 2016.

[16] Rijkswaterstaat, "Wegbeheerders," Rijkswaterstaat, [Online]. Available: https://www.rijkswaterstaat.nl/kaarten/wegbeheerders. [Accessed 2025 February 13].

[17] C. Oliveira and C. X. Silva, "Decarbonisation options for the Dutch asphalt industry," TNO, 2022.

[18] NTP, "Grasfalt, een innovatief asfaltmengsel asfaltmengsel," [Online]. Available: https://ntp.nl/duurzaamheid/grasfalt/. [Accessed 22 November 2024].

[19] K. Mantalovas, G. Di Mino, A. Jimenez Del Barco Carrion, E. Keijzer, B. Kalman, T. Parry and D. Lo Presti, "European National Road Authorities and Circular Economy: An Insight into Their Approaches," *Sustainability,* p. 7160, 2020.

[20] M. C. Rubio, G. Martínez, L. Baena and F. Moreno, "Warm mix asphalt: an overview," *Journal of Cleaner Production,* no. 24, pp. 76-84, 2012.

[21] CROW, „CROW Richtlijn Warm Mix Asphalt v1.0," 2024.

[22] S. Bours, J. Swartjes and M. Hekkert, "Transitie naar een circulaire grond-, weg-, en waterbouw. Een missie-gedreven innovatie systeem analyse," Utrecht University, 2022.

[23] P. Fewings and C. Henjewele, Construction project management, 3th ed., Routledge, 2019.

[24] P. Orihuela, S. Pacheco and J. Orihuela, "Proposal of Performance Indicators for the Design of Housing Projects," *Procedia Engineering,* no. 196, pp. 498-505, 2017.

[25] F. Bijleveld, „Professionalising the asphalt construction process," Enschede, 2015.

[26] S. R. Miller, "Hot mix asphalt construction: towards a more professional approach," Enschede, 2010.

[27] C. Arbeider, S. Miller and M. Oosterveld, "Planning the asphalt construction process - towards more consistent paving and compaction operations," 2017.

[28] R. Kuenzel, J. Teizer, M. Mueller and A. Blickle, "SmartSite: Intelligent and autonomous environments, machinery, and processes to realize smart road construction projects," *Automation in Construction,* pp. 21-33, 2015.

[29] P. Marcelino, M. de Lurdes Antunes and E. Fortunato, "Comprehensive performance indicators for road pavement condition assessment," *Structure and Infrastructure Engineering,* pp. 1433-1445, 2018.

[30] A. Hosseini, A. Faheem, H. Titi and S. Schwandt, "Evaluation of the long-term performance of flexible pavements with respect to production and construction quality control indicators," *Construction and Building Materials,* 2020.

[31] M. Bijleveld, M. Bruinsma, J. de Koning and I. Nieuwenhuijse, "Naar duurzame producten met de principes van circulariteit," CE Delft, Delft, 2023.

[32] Rijkswaterstaat ministerie van infrastructuur en waterstaat, “Duurzaam wegdekonderhoud: "Asphalt Recycling Train' eet oud asfalt op,” 15 March 2024. [Online]. Available: https://www.rijkswaterstaat.nl/nieuws/archief/2024/03/duurzaam-wegdekonderhoud-asfalt-recycling-trein-eet-oud-asfalt-op. [Accessed 20 Novermber 2024].

[33] N. van Rijn, “Elke weg verdient circulair wegdekonderhoud,” Eindhoven, 2024.

[34] Rijkswaterstaat Ministerie van Infrastructuur en Waterstaat, „Roadmap transitiepad Wegverharding,” NewForesight, 2022.

[35] Ministerie van Infrastructuur en Waterstaat, “Roadmap Transitiepad Weg-, Dijk- en Spoormaterieel (WDSM),” NewForesight, 2022.

[36] De Fryske Marren, “Beleidsplan wegbeheer 2020-2024,” 08 July 2020. [Online]. Available: https://lokaleregelgeving.overheid.nl/CVDR642141. [Accessed 3 February 2025].

[37] Provincie Gelderland, “Beheer provinciale infrastructuur 2022-2025,” Provincie Gelderland, 2021.

[38] Rijkswaterstaat, “Missie Rijkswaterstaat,” [Online]. Available: https://www.rijkswaterstaat.nl/over-ons/onze-organisatie/onze-missie. [Accessed 3 February 2025].

[39] European Environment Agency, “Climate change impacts, risks and adaption,” 3 September 2024. [Online]. Available: https://www.eea.europa.eu/en/topics/in-depth/climate-change-impacts-risks-and-adaptation. [Accessed 22 November 2024].

[40] Rijkswaterstaat ministerie van infrastructuur en waterstaat, “Naar klimaat neutrale en circulaire rijksinfrastructuurprojecten,” [Online]. Available: https://www.duurzame-infra.nl/strategie. [Accessed 22 November 2024].

[41] Curia Rationum, “De duurzameontwikkelingsdoelstellingen van de VN in een EU-context,” [Online]. Available: https://www.eca.europa.eu/nl/sustainable-development-goals. [Accessed 21 January 2025].

[42] Europese Raad , “Klimaatverandering: wat onderneemt de EU,” 15 November 2024. [Online]. Available: https://www.consilium.europa.eu/nl/policies/climate-change/. [Accessed 3 February 2025].

[43] Ministerie van Economische Zaken en Klimaat, „Klimaatplan 2021-2030,” Ministerie van Economische Zaken en Klimaat, 2020.

[44] L. Connolly, E. Sheils, M. Lamb, A. O' Connor, E. OBrien, H. Viner, H. Bailey, V. Ramdas and K. Varveri, “Circular economy in road construction and maintenance,” 2023.

[45] Platform CB'23, “Over Platform CB'23,” [Online]. Available: https://platformcb23.nl/. [Accessed 5 February 2025].

[46] KNMI, “KNMI'23 klimaatscenario's voor Nederland,” KNMI, De Bilt, 2023.

[47] A. de Jong, W. Timmerman and C. van Iperen, “Strategisch Assetmanagement Plan Openbare Ruimte 2024-2027,” Gemeente Apeldoorn, 2022.

[48] L. van Hoogevest and P. Derks, Handleiding globale visuele inspectie, Ede: CROW, 2011.

[49] L. van Hoogevest and P. Derks, Handboek visuele inspectie 2011, Ede: CROW, 2011.

[50] R. de Greef and J. Snellink, Beleidsplan wegen gemeente Wierden, 2022.

[51] Gemeente Enschede, Wegenbeleidsplan Enschede 2024-2027, Enschede: Gemeente Enschede, 2023.

[52] M. Aarnink, F. Bouwman and J. Lokate, Beleidsplan Wegen 2023-2028, Hellendoorn: Gemeente Hellendoorn, 2023.

[53] Gemeente Rotterdam, „Assetmanagmentplan Wegen,” Gemeente Rotterdam, 2019.

[54] Y. Wijnia and P. Herder, “The state of asset management in the Netherlands,” in *Proceedings of the 4th World Congress on Engineering Asset Management*, Athens, 2009.

[55] CROW, “Het iAMPro model voor Assetmanagement,” CROW, [Online]. Available: https://essit.nl/over-assetmanagement/wat-is-het-iampro-model-voor-assetmanagement#:~:text=Dit%20iAMPro%20model%20voor%20assetmanagement%20bestaat%20uit%203,processtap%20interacteren%20ook%20met%20de%20de%20overige%20processtappen.. [Accessed 27 February 2025].

[56] P. Verschuren and H. Doorewaard, Designing a Research Project, Second ed., The Hague: Eleven International Publishing, 2010.

[57] W. M. Trochim, J. P. Donnelly and K. Arora, Research Methods - The essential knowledge base, Cengage Learning, 2016.

[58] H. Taherdoost, „How to conduct an effective interview; a guide to interview design in research study,” 2022.

[59] W. W. Cobern and B. A. Adams, “When interviewing: how many is enough?,” *International Journal of Assessment Tools in Education,* pp. 73-79, 2020.

[60] A. Macfarlan, “Validation workshop,” Better evaluation knowledge, 8 July 2024. [Online]. Available: https://www.betterevaluation.org/methods-approaches/methods/validation-workshop. [Accessed 25 February 2025].

[61] Van Diepen Letselschade, “Een analyse van artikel 6:174 BW,” Van Diepen Letselschade, [Online]. Available: https://www.vandiepenletselschade.nl/content/een-analyse-van-artikel-6-174-bw. [Accessed 15 April 2025].

[62] CROW, „Wegbeheer 2019,” 2019. [Online].

[63] A. Fares, T. Zayed, S. Abdelkhalek, N. Faris and M. Muddassir, “Rutting measurement in asphalt pavements,” *Automation in Construction,* no. 161, 2024.

[64] J. Litzka, B. Leben, F. La Torre, A. Weninger-Vycudil, M. d. L. Antunes, D. Kokot, G. Mladenovic, S. Brittain and H. Viner, "The way forward for pavement performance indicators across Europe," COST Action 354, 2008.

[65] O. G. Dela Cruz, C. A. Mendoza and K. D. Lopez, "International Roughness Index as Road Performance Indicator: A Literature Review," *IOP Conference Series: Earth and Environmental Science,* no. 822, 2021.

[66] J. Yu, E. Y. J. Chou and J.-T. and Yau, "Development of Speed-Related Ride Quality Thresholds Using International Roughness Index," *Transportation Research Record: Journal of the Transportation Research Board,* no. 1974, pp. 47-53, 2006.

[67] U. Hammarström, J. Eriksson, R. Karlsson and M.-R. Yahya, "Rolling resistance model, fuel consumption model and the traffic energy saving potential from changed road surface conditions," vti, 2012.

[68] N. Kargah-Ostadi and A. Howard, "Monitoring Pavement Surface Macrotexture and Friction," *Transportation Research Record: Journal of the Transportation Research Board,* no. 2525, pp. 111-117, 2015.

[69] C. Plati, M. Pomoni and T. Stergiou, "Development of a Mean Profile Depth to Mean Texture Depth Shift Factor for Asphalt Pavements," *Transportation Research Record: Journal of the Transportation Research Board,* no. 2641, pp. 156-163, 2017.

[70] A. M. S. H. Shiyab, "Optimum Use of the Flexible Pavement Condition Indicators in Pavement Management System," 2007.

[71] W. Aleadelat and K. Ksaibati, "Estimation of Pavement Serviceability Index Through Android-Based Smartphone Application for Local Roads," *Transportation Research Record: Journal of the Transportation Research Board,* no. 2639, pp. 129-135, 2017.

[72] K. Hall and C. Muñoz, "Estimation of Present Serviceability Index from International Roughness Index," *Transportation Research Record: Journal of the Transportation Research Board,* no. 1655, pp. 93-99, 1999.

[73] C.-G. Wallman and H. Åström, "Friction measurement methods and the correlation between road friction and traffic safety. A literature review.," Swedish National Road and Transport Research Institute, 2001.

[74] R. Schneiderova-Heralova, "Importance of life cycle costing for construction projects," *Engineering for rural development,* pp. 1223-1227, May 2018.

[75] B. Moins, C. France, W. van den Bergh and A. Audenaert, "Implementing life cycle cost analysis in road engineering: A critical review on methodological framework choices," *Renewable and sustainable energy reviews,* August 2020.

[76] U. Sheth, "How to Calculate Social Return On Investment," Sopact, 29 May 2018. [Online]. Available: https://www.sopact.com/perspectives/social-return-on-investment-calculation. [Accessed 28 March 2025].

[77] C. Tate, C. O'Neill, N. Tran, L. Heron, F. Kee, M. A. Tully, M. Dallat and R. F. Hunter, "The social return on investment of an urban regeneration project using real-world data: the

Connswater Community Greenway, Belfast, UK," *Cities & Health,* vol. 7, no. 5, pp. 699-718, 2023.

[78] M. van Weele, "Klimaatneutraal zijn, wat betekent dat?," KNMI, 1 February 2023. [Online]. Available: https://www.knmi.nl/over-het-knmi/nieuws/klimaatneutraal-zijn-wat-betekent-dat. [Accessed 3 March 2025].

[79] J. Vendrik and M. Teng, "Noordenveld Klimaatneutraal 2040 - Wat betekent de doelstelling klimaatneutraal voor de gemeente," CE delft, Delft, 2023.

[80] A. Parry, „A model set of asphalt sustainability indicators," TRL, 2005.

[81] T. van der Kruk and L. Overmars, "Product Category Rules voor bitumineuze materialen in verkeersdragers en waterwerken in Nederland ("PCR Asfalt")," 2022.

[82] A. Schwarz, L. Overmars, D. Godoi, E. Keijzer, L. Kuling and A. van Horssen, "LCA Achtergrondrapport voor branchrepresentatieve Nederlandse asfaltmengsels 2020," TNO, 2020.

[83] P. Prinssen, R. Heuvelmans and S. de Smet, "Stappenplan: inkopen met de MKI - Het behalen van duurzaamheidsdoelstellingen in de GWW," PIANOo, 2024.

[84] Rijkswaterstaat Ministerie van Infrastructuur en Waterstaat, „Roadmap transitiepad Wegverharding," 2022.

[85] Ellen MacArthur Foundation, „Towards the circular economy - Economic and business rationale for an accelerated transition," 2013.

[86] J. Kirchherr, D. Reike and M. Hekkert, "Conceptualizing the circular economy: An analysis of 114 definitions," *Resources, Conservation & Recycling,* pp. 221-232, 2017.

[87] N. van Buren, M. Demmers, R. van der Heijden and F. Witlox, "Towards a Circular Economy: The Role of Dutch Logistics Industries and Governments," *Sustainability,* 2016.

[88] Platform CB'23, „Meten van circulariteit - werkafspraken voor een circulaire bouw," Platform CB'23, 2020.

[89] K. Mantalovas, "Increasing the Circularity of asphalt mixtures: Integrated Sustainability and Circularity Assessment as a progress monitoring tool towards more Circular and Sustainable asphalt," 2021.

[90] Ellen MacArthur Foundation & ANSYS Granta, „Methodology - An approach to measuring circularity," Ellen MacArthur Foundation, 2019.

[91] Platform CB'23, „Meten van circulariteit - Meetmethode voor een circulaire bouw versie 3.0," Platform CB'23, 2022.

[92] S. Liu, "Mapping the road to sustainability: A critical assessment of circularity indicators in pavement infrastructure," TU Delft, Delft, 2024.

[93] M. Lamb, H. Viner, V. Ramdas, H. Bailey, L. Connolly, O. C. Alan and E. Sheils, "Good practice inventory of current systems and procurement methods," CERCOM, 2022.

[94] Duurzame infra en SEB, "Geld besparen dankzij levensduurverlengend wegonderhoud," Binnelands Bestuur, 2 April 2024. [Online]. Available: https://www.binnenlandsbestuur.nl/ruimte-en-milieu/duurzame-infra-en-seb/met-levensduurverlengend-wegonderhoud-geld-besparen. [Accessed 28 March 2025].

[95] Kennisportaal Klimaatadaptatie, "Wegen," Stichting Climate Adaptation Services, [Online]. Available: https://klimaatadaptatienederland.nl/kennisdossiers/infrastructuur/wegen/. [Accessed 7 February 2025].

[96] A. Mohajerani, J. Bekaric and T. Jeffrey-Bailey, "The urban heat island effect, its causes, and mitigation, with reference to the termal properties of asphalt concrete," *Journal of Environmental Management,* pp. 522-538, 2017.

[97] H. Visser, L. Tolk, V. Beumer and D. van Hout, "Handreiking Klimaatadaptieve én Natuurinclusieve Wegen," Aveco de Bondt, 2022.

[98] Ministerie van Infrastructuur en Waterstaat; Ministerie van Landbouw, Visserij, Voedselzekerheid en Natuur; Ministerie van Volkshuisvesting en Ruimtelijke Ordening, „Nationaal Deltaprogramma 2025 - Naar een nieuwe balans in de leefomgeving: Ruimte voor leven met water," Ministerie van Infrastructuur en Waterstaat; Ministerie van Landbouw, Visserij, Voedselzekerheid en Natuur; Ministerie van Volkshuisvesting en Ruimtelijke Ordening, 2024.

[99] H.-O. Pörtner, D. Roberts, E. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller and A. Okem, "Technical Summary," *Climate Change 2022 – Impacts, Adaptation and Vulnerability,* pp. 37-118, 22 Juni 2023.

[100] A. Choate, B. Dix, B. Rodehorst, A. Wong, W. Jaglom, J. Keller, J. Lennon, D. Chris, R. Kuchibhotla, J. Mallela and S. Sadasivam, "Synthesis of Approaches for Addressing Resilience in Project Development," U.S. Department of Transportation Federal Highway Administration, 2017.

[101] M.-S. Song, S.-G. Yum, H.-S. Yun, S.-H. Park, S.-W. Bae and J.-J. Lee, "Development of an evaluation indicator for highway climate change adaptation projects based on analytical hierarchy process in South Korea," *Meteorological Applications,* 2024.

[102] L. Klok, L. Kleerekoper, J. Kluck and E. C. Barbosa, "Het is heet onder onze voeten," 2022.

[103] CROW, "Asfalt in de weg- en waterbouw," 8 January 2021. [Online]. [Accessed April 2025].

[104] Z. Ma, J. Zhang, S. Philbin, H. Li, J. Yang, Y. Feng, P. Ballesteros-Pérez and M. Skitmore, "Dynamic Quality Monitoring System to Assess the Quality of Asphalt," *Buildings,* 24 November 2021.

[105] L. Lu, F. Dai and J. P. Zaniewski, "Automatic roller path tracking and mapping for pavement compaction using infrared thermography," *Computer-Aided Civil and Infrastructure Engineering,* no. 36, pp. 1416-1434, 24 November 2021.

[106] S. Miller, H. ter Huerne, A. Dorée and B. Sluer, "Op weg naar verdere professionalisering Monitoring A35," 2008.

[107] IBM, "What is infrastructure asset management (IAM)?," IBM, 3 August 2023. [Online]. Available: https://www.ibm.com/think/topics/infrastructure-asset-management. [Accessed 28 February 2025].

[108] M. G. Correia and A. Ferreira, "Road Asset Management and the Vehicles of the Future: An Overview, Oppertunities, and Challenges," *International Journal of Intelligent Transportation Systems Research,* pp. 376-393, 2023.

[109] R. Roozbeh, M. Michael, R. Neil and K. Karolina, "Unleashing the cont savings of optimized road asset management to municipalities," Vancouver, 2017.

[110] F. Giustozzi, M. Crispino and G. Flintsch, "Multi-attribute life cycle assessment of preventive maintenance treatments on road pavements for achieving environmental sustainability," *The International Journal of Life Cycle Assessment,* vol. 17, pp. 409-419, 2012.

[111] CROW, "Road Monitoring (ROMO)," CROW, [Online]. Available: https://essit.nl/pagina/road-monitoring-romo. [Accessed 3 March 2025].

[112] Platform CB'23, "Leidraad Paspoorten voor de bouw," Platform CB'23, June 2023. [Online]. Available: https://platformcb23.nl/wp-content/uploads/PlatformCB23_Leidraad_Paspoorten-voor-de-bouw.pdf.

[113] D. Makarov, S. Miller, F. Vahdatikhaki and A. Dorée, "Comprehensive real-time pavement operation support system using machine-to-machine communication," Springer, 2019.

[114] Univrses, "The Swedish Transport Administration," 24 September 2024. [Online]. Available: https://univrses.com/newsroom/case-studies. [Accessed 28 February 2025].

[115] L. Fuenfschilling and B. Truffer, "The interplay of institutions, actors and technologies in socio-technical systems - An analysis of transformations in the Australian urban water sector," *Technological Forecasting & Social change,* 312 298 2016.

[116] T. Lawrence and R. Suddaby, "Institutions and Institutional Work," *Sage Handbook of Organization Studies,* pp. 215-254, 2006.

[117] R. Kitchin, S. Maalsen and G. McArdle, "The praxis and politics of building urban dashboards," *Geoforum,* vol. 77, pp. 93-101, 2016.

[118] M. Tantillo, K. Smith, C. Packard, T. Lomax and S. Dhuri, "Transportation Management Center Performance Dashboards," U.S. Department of Transportation Federal Highway Administration, 2021.

[119] D. Orts, "Dashboard Development and Deployment A Methodology for Success," Noetix Corporation, 2004.

APPENDIX A – INTERVIEW PROTOCOL

Datum:
Begintijd interview:
Eindtijd interview:

Naam geïnterviewde:
Functie geïnterviewde:
Organisatie waar de geïnterviewde werkt:
Toestemming voor het opnemen van het interview: ja/nee

Interview protocol

Stap 1: Omschrijving onderzoeksdoel & vraag

Ik ben Aniek en ben momenteel bezig met mijn Master Thesis voor de studie civiele techniek aan de Universiteit Twente. In mijn afstudeeronderzoek probeer ik inzicht te creëren in welke indicatoren/gegevens assetmanagers in Nederland nodig hebben om keuzes te maken met betrekking tot wegonderhoud en om hun doelen te bereiken. Ik heb begrepen dat asset managers momenteel veel keuzes maken op basis van hun eigen kennis maar dat er geen standaard keuze proces is die door elke assetmanager in Nederland wordt gebruikt. Daarom voer ik nu interviews uit met verschillende asset managers om inzicht te krijgen in de indicatoren en gegevens die zij nu gebruiken om keuzes te maken met betrekking tot asset management. Het doel van mijn afstudeeropdracht is om deze indicatoren en gegevens uiteindelijk te verzamelen zodat dit gebruikt kan worden om keuzes van asset managers inzichtelijker te maken.

Stap 2: Vermeld namen van betrokken partijen

Dit onderzoek wordt gedaan in samenwerking met de Universiteit Twente en de Wegverleggers.

Stap 3: Uitleggen doel en de manier waarop de gegevens worden gebruikt

De gegevens worden gebruikt om inzicht te creëren in de taken die assetmanagers uitvoeren, de doelen en indicatoren die zij hebben en welke informatie zij nodig hebben om weloverwogen keuzes te maken met betrekking tot asset management.

Stap 4: Uitleggen proces dat gevolgd wordt tijdens het interview

Ik heb een lijstje met vragen die ik u graag wil stellen. Het interview is semigestructureerd opgesteld wat inhoud dat ik u vervolgvragen kan stellen of dat u dingen toe kunt voegen mocht u dat willen.

Stap 5: Vragenlijst

Rol en definitie asset manager

1) Wat is uw rol en bandbreedte binnen de organisatie waar u werkt?

2) Hoe zien uw werkzaamheden als assetmanager eruit?

3) Hoe zou u asset management beschrijven?

Doelen asset manager

4) Welke doelen wilt u graag behalen als assetmanager zijnde?

5) Aan welke eisen moet een weg voor u doen?

Indicatoren om doelen te meten en keuzes te maken

6) Welke indicatoren (KPI's) gebruikt u als assetmanager om te meten of u uw doelen haalt en om strategische keuzes te maken? (e.g. de stroefheid van de weg voor veiligheid). En hoe worden deze indicatoren gebruikt in de verschillende fases van de levensduur van de weg; ontwerp, productie, transport, constructie, gebruiksfase en einde-levensduur?

   Ontwerp:

   Productie:

   Transportfase:

   Constructie:

   Gebruiksfase:

   Einde levensduur:

Indicatoren om doelen te meten en keuzes te maken

7) Hoe heeft u deze indicatoren bepaald/ vastgesteld?

8) Zijn deze indicatoren kwalitatief of kwantitatief en waarom?

9) Welke indicatoren vindt u het meest cruciaal voor het behalen van de strategische doelstellingen die u hebt?

10) Hoe neemt u de doelstellingen die veel overheden hebben mee in uw keuzes en welke indicatoren gebruikt u hiervoor? (bijvoorbeeld circulariteit, CO2, integrale ontwikkelingen, klimaat adaptief, een gezonde leefomgeving, etc.).

    a. Hoe neemt u circulariteit mee in uw keuzes als assetmanager en in de gebruikte indicatoren?

    b. Hoe neemt u CO_2 neutraliteit mee in de keuzes die u maakt als assetmanager en in de gebruikte indicatoren?

Indicatoren om doelen te meten en keuzes te maken

c. Hoe neemt u integrale ontwikkelingen mee in de keuzes die u maakt als asset manager en in de gebruikte indicatoren?

d. Hoe neemt u klimaat adaptatie mee in uw keuzes als asset manager en in de gebruikte indicatoren?

e. Hoe neemt u een gezonde leefomgeving mee in de keuzes die u maakt als asset manager en in de gebruikte indicatoren?

f. Zijn er nog andere doelenstellingen die u meeneemt in de keuzes die u maakt als asset manager en in de gebruikte indicatoren?

11) Welke indicatoren missen er nu nog volgens u?

Priorisering in keuzes

12) Hoe prioriteert u welke wegen als eerste onderhoud nodig hebben?

13) Welke risicofactoren hanteert u bij de afweging van uw keuzes?

14) Heeft klimaatverandering impact op de keuzes die u maakt in uw werk? En waarom?

Monitoring conditie wegen / data verzameling

15) Hoe monitort u momenteel de conditie van wegen? En hoe vaak per jaar?

16) Is deze manier van monitoring volgens u voldoende om goed weg onderhoud te leveren en is het aantal monitor momenten voldoende?

17) Welke data gebruikt u momenteel als asset manager? En waar wordt deze data momenteel opgeslagen?

18) Wordt deze data ook gebruikt om indicatoren of presentaties te monitoren? Zoja, hoe? Zo nee, waarom niet?

19) Welke data heeft u momenteel nog niet, maar zou wel nuttig zijn om uw werk beter uit te voeren?

20) Gebruikt u ook nog data met die verzameld is tijdens het aanlegproces van de weg? Zoja, welke data? Zo nee, zou deze data nuttig voor u zijn?

21) Gebruikt u ook omgevingsdata/indicatoren? En zou het nuttig zijn om hier indicatoren/ data over te hebben?

22) Hoe staat u tegenover data-gedreven onderhoud?

Bronnen

23) Welke literatuur gebruikt u nu om keuzes te maken?

24) Welke bronnen adviseert u mij om in te kijken om meer inzicht te krijgen in indicatoren, eisen of data die nodig is voor goed asset management?

De toekomst

25) Stel er wordt een dashboard gemaakt met indicatoren en eisen die helpt om betere keuzes te maken als assetmanager, welke indicatoren en eisen zouden hier dan op moeten staan volgens u?

26) Welke score zouden deze indicatoren volgens u moeten hebben? Is er een bepaalde schaal om deze indicatoren te meten en een bepaalde norm die bereikt moet worden?

27) Welke aanpassingen of innovaties zouden er volgens u nodig zijn om de meetbaarheid van de assetmanagementdoelen verder te verbeteren?

28) Hoe ziet die assetmanager van de toekomst eruit volgens u en hoe moet zijn manier van keuzes maken eruitzien? Ziet dit er anders uit dan de huidige manier van werken?

Overige

29) Heeft u nog aanvullende opmerkingen?

STAP 6: Snowball sampling

Zijn er nog andere personen die u kent die ik mogelijk ook nog kan interviewen en die mij nog verdere inzichten kunnen geven voor mijn onderzoek?

Stap 7: Bedanken geïnterviewde

Bedankt voor het interview. Mocht u nog verdere vragen hebben aan mij met betrekking tot dit interview of nog dingen tegen komt die voor mijn onderzoek nuttig zijn dan hoor ik het graag. U kunt altijd contact opnemen via: ….. of mij bellen op ………..

Appendix B – Invitation workshop

Beste allemaal,

Hierbij wat aanvullende informatie over de workshop op woensdag 23 april 2025.

De workshop vindt plaats aan de **Kerkstraat 4 in Losser** en start om **8:30 uur**. We ronden naar verwachting af rond 12:30 uur.

Tijdens de sessie zal ik eerst een presentatie geven over de voorlopige bevindingen uit mijn onderzoek. Aansluitend volgt een interactief deel, waarin we in gesprek gaan over hoe asset managers strategischer kunnen werken. Hierbij richten we ons op indicatoren die nodig zijn voor het realiseren van doelen op het gebied van onder andere wegenkwaliteit, circulariteit, klimaatadaptatie en klimaatneutraliteit.

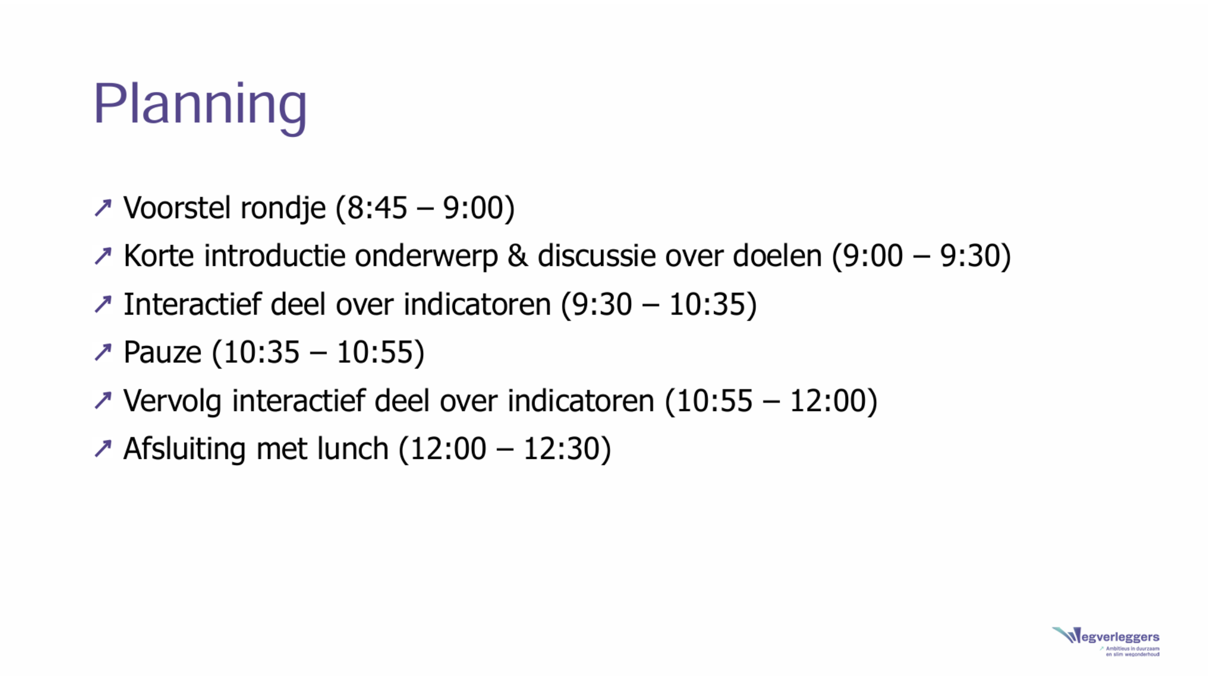
Het doel van de workshop is om inzichten te delen en om van elkaar te leren.

Mocht je nog vragen hebben, dan hoor ik het graag.

Met vriendelijke groet,

Aniek Hollander

APPENDIX C – WORKSHOP SLIDES



Voorstelronde

↗ Je naam, organisatie, en functie

Wegverleggers

Presentatie

↗ Doel van het onderzoek, asset management, bevindingen tot nu toe

Wegverleggers

Doel van het onderzoek

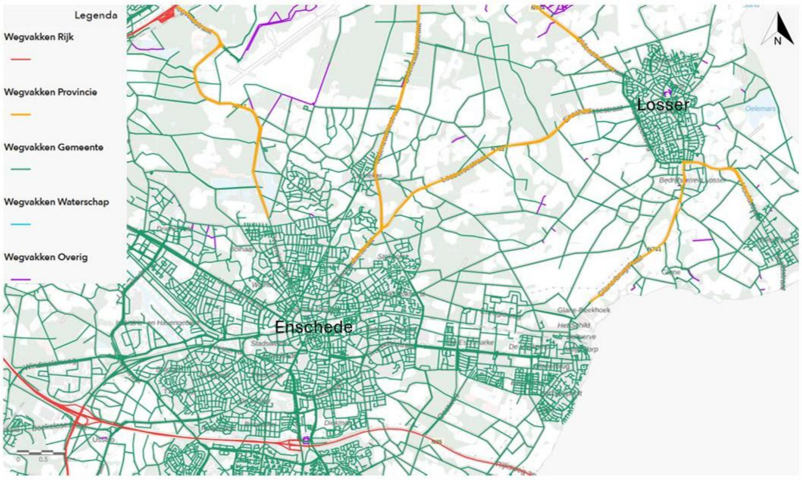
Probleem: Keuzes worden vooral gemaakt op basis van impliciete kennis van assetmanagers en om de doelstellingen van asset managers te behalen zijn er indicatoren en data nodig om strategischere keuzes te maken

Doel: Het creëren van inzicht in welke indicatoren, data en veranderingen er nodig zijn voor asset managers van gemeentelijke wegen om strategischere keuzes te maken

Onderzoeksvraag: Welke indicatoren, gegevens en veranderingen zijn er nodig om te meten of doelen van de asset managers van de toekomst worden gehaald en om strategischere keuzes te maken?

Scope: Gemeentes en asfaltverharding

Verantwoordelijke partijen wegen

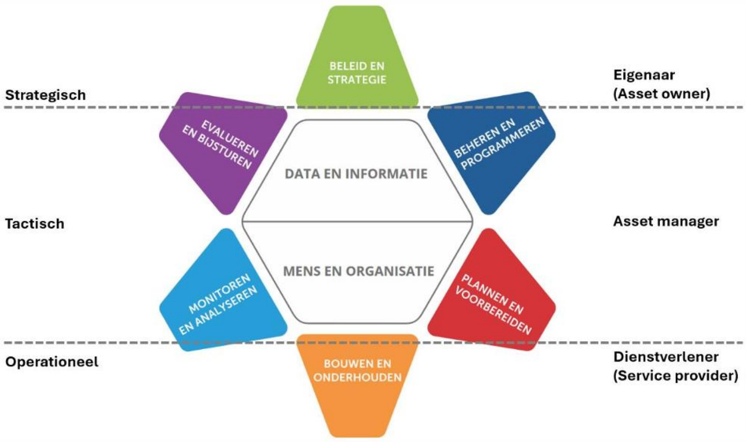


Verplichtingen Asset Managers

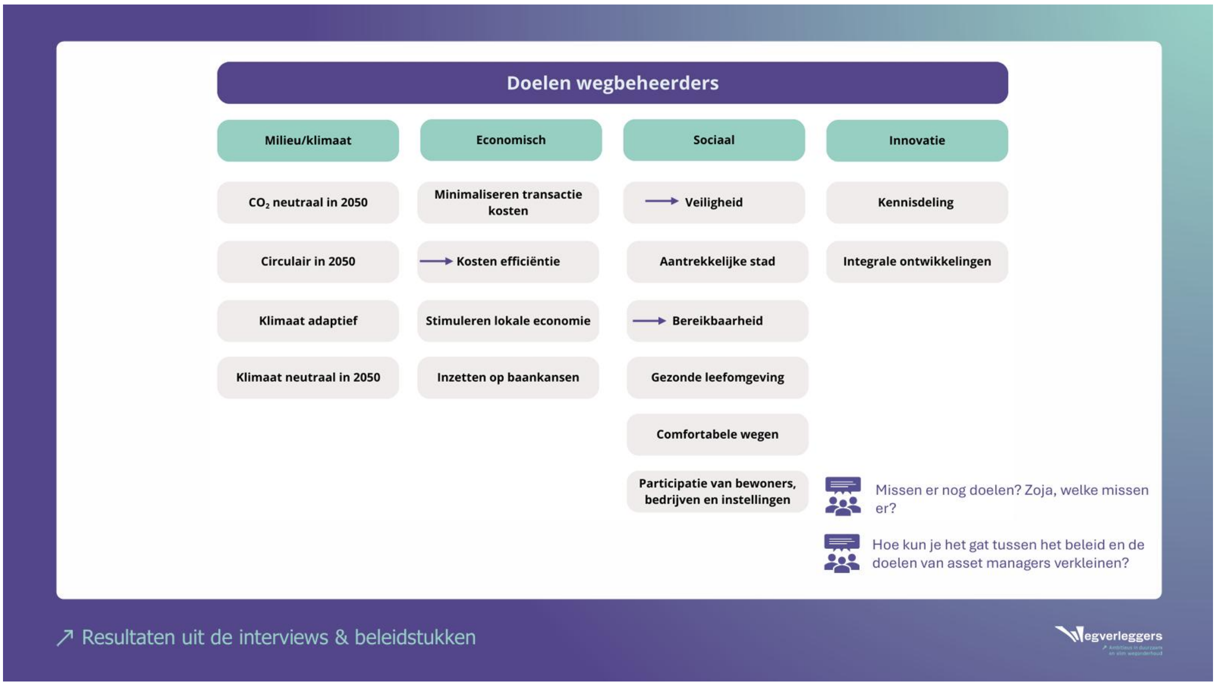
Artikel 16 van de wegenwet

"De gemeente heeft te zorgen, dat de binnen haar gebied liggende wegen, met uitzondering van de wegen, welke door het Rijk of eene provincie worden onderhouden, van die bedoeld in artikel 17 en van die, waarop door een ander tol wordt geheven met uitzondering van de gemeentelijke wegen, genoemd in de bijlage bij de Wet vrachtwagenheffing, verkeeren in goeden staat."

Asset management



Bron: aangepast figuur van de CROW
Link: Wat is het iAMPro model voor assetmanagement? | CROW Essit


Doelen wegbeheerders
Milieu/klimaat
Economisch
Sociaal
Innovatie
CO2 neutraal in 2050
Minimaliseren transactie kosten
Veiligheid
Kennisdeling
Circulair in 2050
Kosten efficiëntie
Aantrekkelijke stad
Integrale ontwikkelingen
Klimaat adaptief
Stimuleren lokale economie
Bereikbaarheid
Klimaat neutraal in 2050
Inzetten op baankansen
Gezonde leefomgeving
Comfortabele wegen
Participatie van bewoners, bedrijven en instellingen
Missen er nog doelen? Zoja, welke missen er?
Hoe kun je het gat tussen het beleid en de doelen van asset managers verkleinen?
↗ Resultaten uit de interviews & beleidstukken
Wegverleggers


Indicatoren & data
↗ Technisch, klimaat-neutraliteit, circulariteit, klimaatadaptatie, kosten, product en productie kwaliteit
Wegverleggers

Technische indicatoren

↗ Veiligheid, aanzien, duurzaamheid en comfort

Indicatoren Technische Kwaliteit

Huidige situatie

- Visuele CROW indicatoren gebaseerd op de ernst en omvang van schades
  - Rafeling
  - Dwarsonvlakheid
  - Oneffenheden
  - Scheurvorming
  - Zetting
  - Randschade
- Schade meldingen bewoners

Mogelijke extra indicatoren en data volgens literatuur

- Rut depth
- International Roughness Index
- Mean Profile Depth
- Pavement Serviceability Index
- Pavement Condition Index
- Valgewichtdeflectiemetingen
- Friction Index

Behoefte en belemmeringen

Behoefte: Er is behoefte aan objectievere en gedetailleerdere indicatoren voor de technische kwaliteit van wegen die ook visueel weergegeven kunnen worden.

Belemmeringen: Metingen zijn vaak duur en data over schades gedetailleerder opschrijven kost ook meer geld. De kosten moeten opwegen tegen de opbrengsten.

Klopt het dat jullie behoefte hebben aan objectievere en gedetailleerdere indicatoren voor de technische kwaliteit van wegen?

Zijn er nog andere belemmeringen die jullie zien? Wat moet er veranderen om in de behoefte te voorzien met betrekking tot technische kwaliteit?

Kosten indicatoren

↗ Kosten efficiënt werken

Wegverleggers

Indicatoren Kosten

Huidige situatie

- Levenscycluskosten missen vaak
- Jaarlijkse kosten om de onderhoudsstrategie uit te voeren
- Kapitaalvernietiging – uitdaging om gepland onderhoud aan andere assets mee te nemen
- Onderhoudsachterstand
- Onderhoudskosten per vierkante meter weg

Mogelijke extra indicatoren en data volgens literatuur

- Levenscycluskosten – Equivalent Uniform Annual Cost indicator
- Milieu en sociale opbrengsten uitgedrukt in een monetaire waarde vergeleken met de extra investeringskosten

Behoefte en belemmeringen

Behoefte: Er is een kostenindicator nodig die rekening houdt met de gehele levenscyclus en er is behoefte aan data over onderhoud aan andere assets zodat kapitaalvernietiging voorkomen kan worden

Belemmeringen:

- Er is kennis nodig om de levenscycluskosten te berekenen en de denkwijze moet veranderen van reactief naar proactief
- Levenscycluskosten zijn gebaseerd op voorspellingen en deze voorspellingen moeten accuraat zijn
- Data over de lange termijn planningen voor onderhoud aan andere assets is vaak niet centraal opgeslagen

Klopt het dat jullie behoefte hebben aan een kosten indicator die rekening houd met de gehele levensduur van een weg?

Klopt het dat jullie behoefte hebben aan data over de lange termijn planning voor onderhoud aan andere assets?

Zijn er nog andere belemmeringen die jullie zien? Wat moet er veranderen om in de behoefte te voorzien met betrekking tot kosten?

Wegverleggers

Klimaat neutraal

↗ Netto uitstoot moet 0 zijn; CO_2, CH_4, N_2O, HFK, SF_6 en PFKs

Wegverleggers

Indicatoren klimaat neutraal

Huidige situatie

- Er zijn geen indicatoren die direct klimaat-neutraliteit meten
- Energie verbruik (in de productie van asfalt) per ton asfalt
- Aantal verminderde transport bewegingen
- Emissies berekend voor verschillende levenscyclusfases met de Product Category Rules
- Milieu Kosten Indicator (MKI) berekend met de Product Category Rules

Mogelijke extra indicatoren en data volgens literatuur

- Extra brandstof verbruik door een hogere rolweerstand die afhankelijk is van de IRI en de MPD
- Alle broeikasgassen uitgedrukt in CO2 Equivalenten

Behoefte en belemmeringen

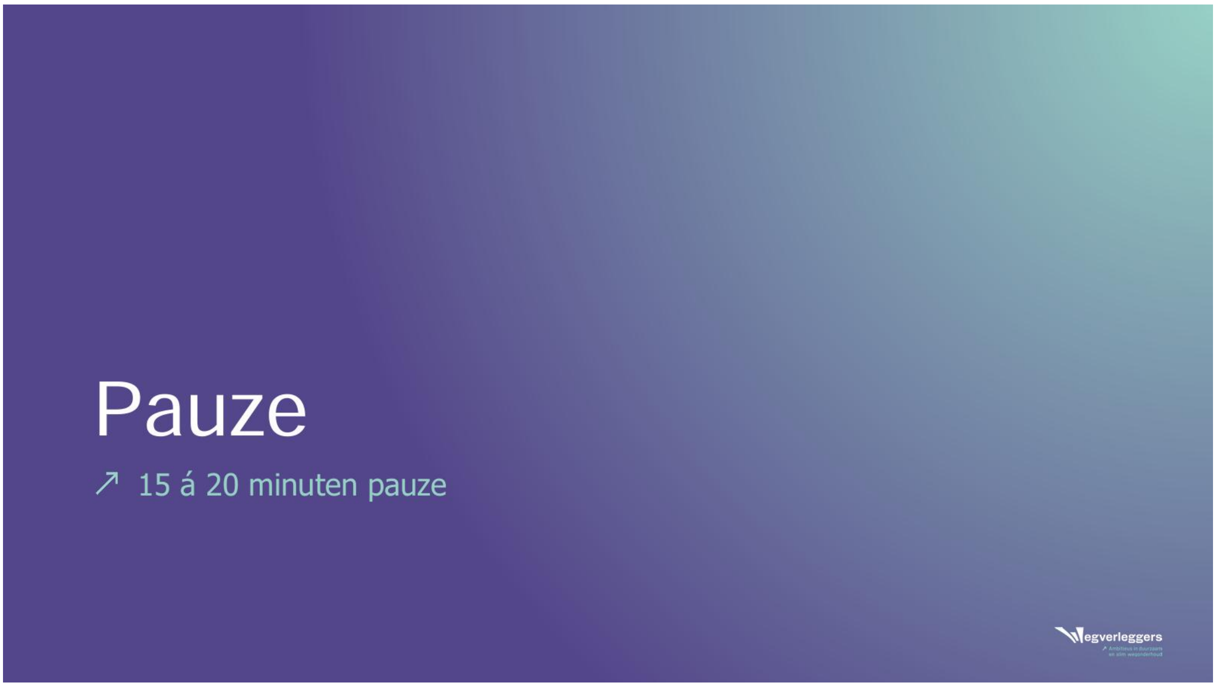
Behoefte: Indicatoren die alle emissies omvatten die klimaatverandering beïnvloeden (CO2, CH4, N2O, SF6, NF3, HFK, PFK's) over de gehele levensduur van een weg en die oplossings-neutraal zijn.

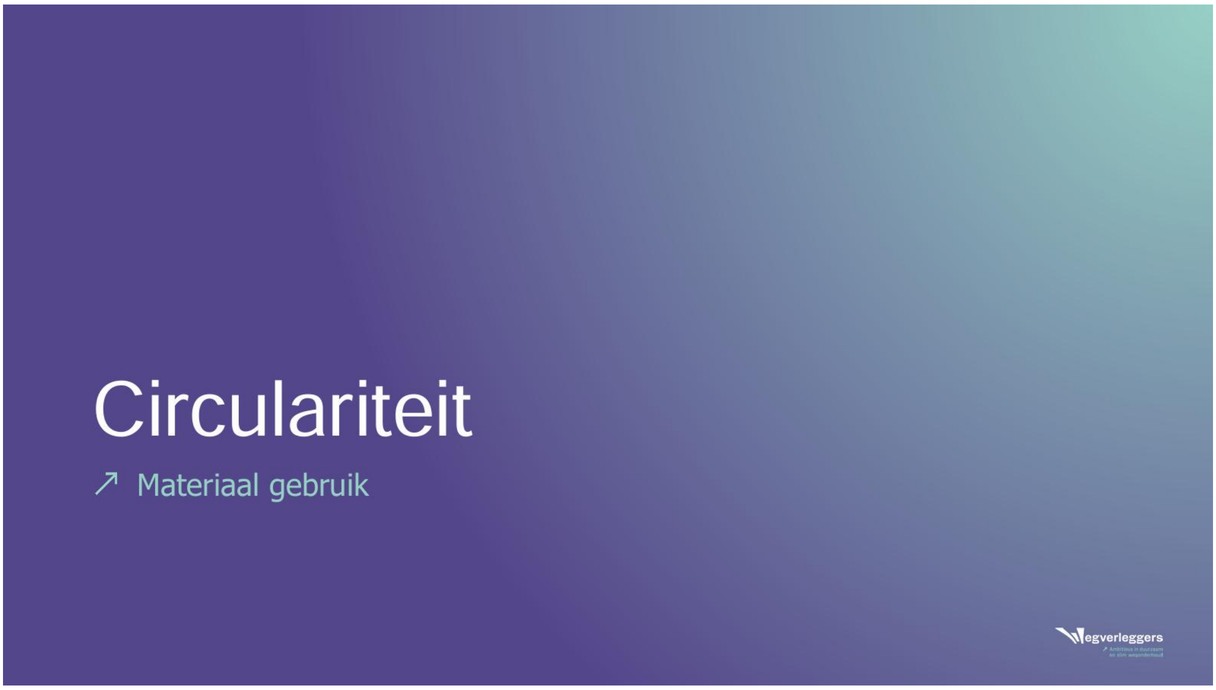
Belemmeringen:

- Er is een methode nodig om de uitstoot over de gehele levensduur van een weg te bepalen
- Er is een langetermijnperspectief nodig en langetermijnstrategieën moeten tegen elkaar afgewogen worden.
- De prioriteit van sommige asset managers ligt niet op het klimaat neutraal worden

Zijn er nog andere belemmeringen die jullie zien? Wat moet er veranderen om in de behoefte te voorzien met betrekking tot klimaat neutraliteit?

Wegverleggers


Pauze
↗ 15 á 20 minuten pauze
Wegverleggers


Circulariteit
↗ Materiaal gebruik
Wegverleggers

Indicatoren Circulariteit

Huidige situatie

- Circulariteit wordt beperkt meegenomen in keuzes
- Ad-hoc gebruik van indicatoren:
  - Percentage gerecycled asfalt
  - Percentage biobased-bindmiddelen
  - Milieu Kosten Indicator (MKI)
- Definitie van circulariteit varieert tussen asset managers
- Langetermijn perspectief mist soms (bijv. preventief onderhoud)

Mogelijke indicatoren en data

- De indicatoren van platform CB'23
- Material Circularity Index (MCI)
- Levensduurverlenging ("Repair")
- De gereduceerde hoeveelheid materialen vergeleken met traditionele werkmethodes

Behoefte en belemmeringen

Behoefte: Data over materiaal gebruik in wegen. Indicatoren die minder gericht zijn op een oplossing en focussen op alle aspecten van het R-kader;

(1) Refuse, (2) Reduce, (3) Reuse, (4) Repair, (5) Refurbish, (6) Remanufacture, (7) Repurpose, (8) Recycle en (9) Recover energy.

Belemmeringen: Er zijn duidelijke definities nodig voor bijvoorbeeld hergebruik en recyclen en een uniforme data verzamelingsmethode is nodig

Zijn er nog andere belemmeringen die jullie zien? Wat moet er veranderen om in de behoefte te voorzien met betrekking tot circulariteit?

Wegverleggers

Klimaat adaptatie

↗ Aanpassen op veranderend klimaat

Wegverleggers

Indicatoren klimaatadaptatie

Huidige situatie

Er zijn nauwelijks indicatoren voor klimaat adaptatie

Klimaatverandering zorgt bijvoorbeeld voor:
- Hittestress
- Overstromingen
- Uitdroging van de grond
- Bermbranden

Mogelijke extra indicatoren en data

- In de literatuur zijn weinig indicatoren te vinden met betrekking tot klimaat adaptatie in de wegenbouw sector
- De stappen die nodig zijn voor de besluitvormingsstrategie voor klimaatadaptatie staan in de literatuur
- Volumetoename wateropslag (m^3)
- Kans op schade door bodemdaling
- Gemiddelde stijging/daling van de oppervlaktetemperatuur van de weg als gevolg van onderhoud (°C)

Behoefte en belemmeringen

Behoefte: SMART doelen en indicatoren voor klimaat adaptatie

Belemmeringen: Klimaat adaptatie wordt beïnvloed door veel factoren en het is uitdagend SMART doelstellingen te maken door de afhankelijkheid van de locatie

Zijn er nog andere belemmeringen die jullie zien? Wat moet er veranderen om in de behoefte te voorzien met betrekking tot klimaat adaptatie?

Wegverleggers

Product en productie kwaliteit

↗ Productie en product kwaliteit is waar het allemaal begint

Wegverleggers

Indicatoren product en productie kwaliteit

Huidige situatie

- De dichtheid van het asfalt wordt momenteel bepaald door boorkernen met een diameter van 100 mm te gebruiken
- In-situ metingen van de stroefheid van de weg
- In-situ meting van de vlakheid van de weg
- Temperatuur metingen van het asfalt in de asfalt centrale
- Huidige focus is op productkwaliteit

Mogelijke extra indicatoren en data volgens literatuur

- Indicatoren die inzicht geven in proceskwaliteit
  - Temperatuur verschillen tijdens het aanlegproces van de weg
  - Het aantal walsgangen per locatie tijdens het verdichtingsproces

Behoefte en belemmeringen

Behoefte: Gegevens om beter inzicht te krijgen in de kwaliteit van het asfalt en in zwakke plekken zodat betere voorspellingen kunnen worden gemaakt over de levensduur van de weg

Belemmeringen: Er moeten meer gegevens worden verzameld door asset managers over het aanlegproces van de weg in samenwerking met aannemers

Zijn er nog andere belemmeringen die jullie zien? Wat moet er veranderen om in de behoefte te voorzien met betrekking tot meer data over proceskwaliteit?

Wegverleggers

Reflectie op mijn bevindingen tot dusver:

- ↗ Een duidelijk **strategisch asset managementplan** is nodig met doelstellingen die **SMART** zijn geformuleerd met bijbehorende indicatoren. Deze indicatoren moeten waar mogelijk **oplossingsneutraal** zijn en direct inzicht geven in het doel.
- ↗ **Educatie** is nodig over duurzaamheidsdoelstellingen zodat het gat tussen beleid en praktijk wordt gedicht
- ↗ Denkwijze moet veranderen van **reactief** naar **preventief** door **tools** te ontwikkelen die inzicht geven in de voordelen van preventief onderhoud
- ↗ Innovaties zijn nodig om:
  - ↗ **Objectievere** en **gedetailleerdere** data over de condities van wegen te verzamelen op een betaalbare manier
  - ↗ Betere voorspellingen te maken van de **verwachte levensduur** van de weg
  - ↗ Betere **lange termijn onderhoudsplanningen** te maken waarin **verschillende doelen** tegen elkaar afgewogen worden
- ↗ Er moet een **uniforme** manier komen waarop **data** over duurzaamheidsdoelstellingen wordt verzameld en verwerkt. Ik denk dat gemeentes **gezamenlijk** een uniforme manier moeten bedenken waarop dit kan worden gedaan in samenwerking met aannemers.

↗ Reflectie

Wegverleggers

Afsluiting workshop

↗ Zijn er nog vragen of aanvullende opmerkingen?

APPENDIX D – CONCEPTUAL DASHBOARD

This section presents a conceptual dashboard created by the author of this thesis, based on insights from the interviews (see Figure 12). It is intended solely as a source of inspiration for municipal asset managers. Each municipality should determine for itself which indicators are relevant for them and how to implement a dashboard that aligns with their specific data structure.

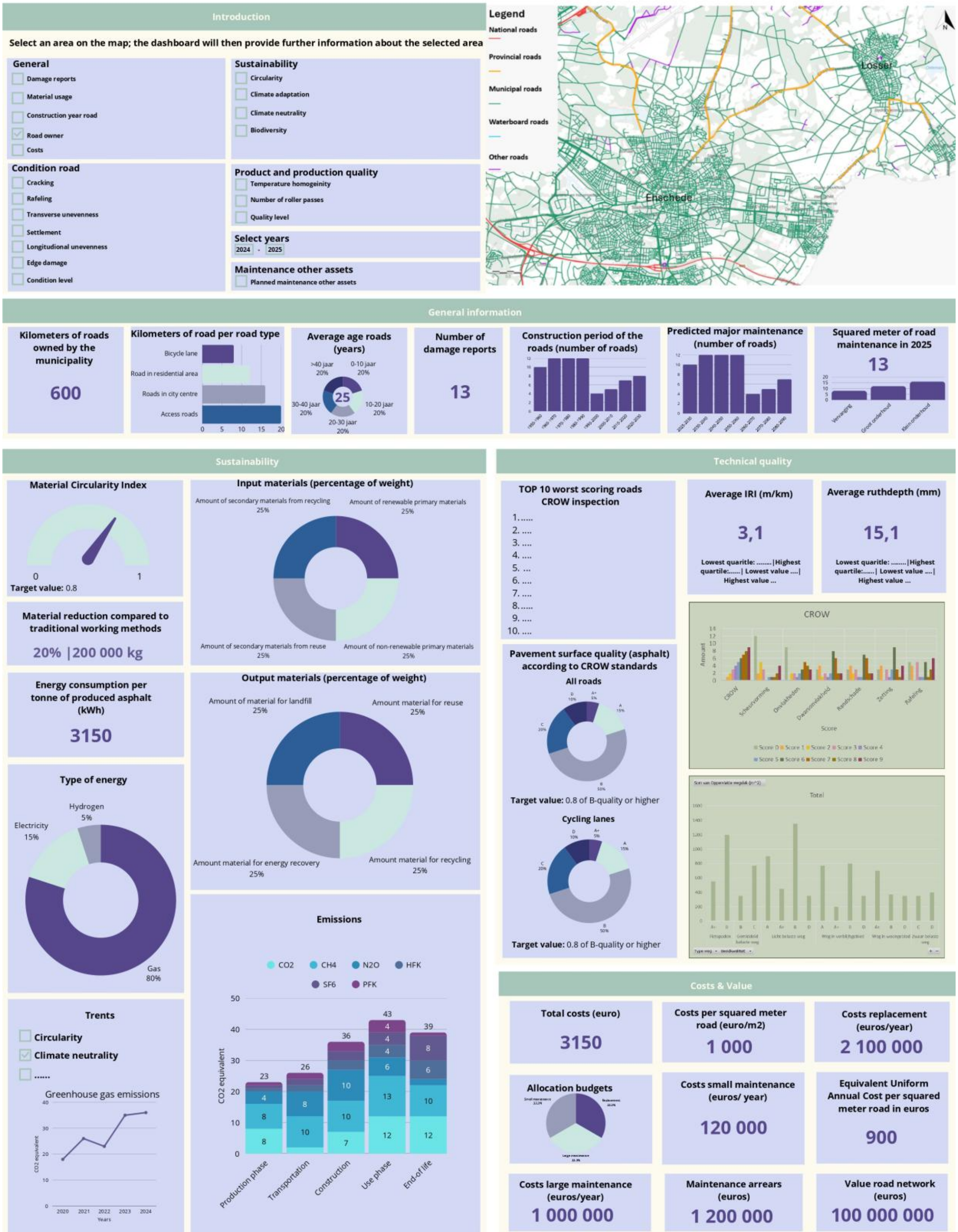


Figure 12 - Conceptual dashboard