Universiteit Twente – Ballast Nedam

Spatial and Temporal Dynamics of Reclaimed Asphalt Pavement (RAP) Material Flows: The Impact of a Regional Asphalt Bank in the Amsterdam Transport Region

Report: MSc Thesis – Project Report

Boyd Lubbers

October 7, 2024

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Preface

You are about to read my Master's Thesis titled *"Spatial and Temporal Dynamics of Reclaimed Asphalt Pavement (RAP) Material Flows: The Impact of a Regional Asphalt Bank in the Amsterdam Transport Region."* This research was commissioned by Ballast Nedam Road Specialties and was completed to fulfil the graduation requirements of the Construction Management and Engineering (CME) master's program at the University of Twente in Enschede, the Netherlands. The research and writing process took place from January to August 2024.

This thesis journey has been both challenging and rewarding, pushing me to expand my knowledge and skills in ways I had not anticipated. I delved into new techniques and programs, often starting from nothing, particularly with Python-MIP and Mixed Integer Linear Programming. Additionally, I gained substantial experience in setting up, conducting, and processing interviews, which has significantly improved my proficiency in this area. Above all, I learned that facing and overcoming struggles is an integral part of the process, and this experience has imparted valuable lessons, both professionally and personally.

I want to thank my supervisors at the University of Twente, Dr. Seirgei Miller and Dr. João Miguel Oliveira dos Santos, for their guidance and support throughout this somewhat unconventional thesis process. Their insights provided both practical and theoretical foundations that served as a strong basis for this Master Thesis. I am also thankful to my external supervisors at Ballast Nedam Road Specialties, Jan van de Water and ir. Radjan Khedoe, for sharing their practical and technical knowledge of the asphalt supply chain, as well as for their valuable industry connections. My appreciation extends to the other colleagues at Ballast Nedam Road Specialties, whose knowledge and the pleasant working atmosphere made this journey enjoyable. I also want to thank the individuals who participated in the interviews, generously sharing their knowledge, insights, and perspectives on the asphalt supply chain.

Lastly, I want to thank my family for their constant support during this thesis journey and for being there during challenging times. And to you, the reader, for taking the time to engage with my work. I hope you find it insightful and enjoyable.

Boyd Lubbers
Markelo, October 7, 2024

Samenvatting

Deze masterthesis onderzoekt de potentiële impact van een regionale asfaltbank op de ruimtelijke en tijdsgebonden dynamiek van asfaltgranulaat (Reclaimed Asphalt Pavement, RAP) binnen de Vervoerregio Amsterdam. Het draagt bij aan de duurzaamheidsdoelstellingen van de Nederlandse asfaltsector, zoals opgesteld door Rijkswaterstaat naar aanleiding van de klimaatdoelstellingen van de Nederlandse overheid en het Klimaatakkoord van Parijs. De studie richt zich op de uitdagingen bij het hoogwaardig recyclen van asfaltgranulaat, met name om de recyclingpercentages in de asfaltdeklagen te verhogen, en onderzoekt hoe een asfaltbank de ruimtelijke en tijdsgebonden distributie van asfaltgranulaat kan beïnvloeden.

Het onderzoek werd uitgevoerd in drie fasen: inventarisatie, analyse en modellering. In de eerste fase werden gegevens verzameld en geanalyseerd over het huidige wegennet en de asfaltketen, inclusief geografische, geometrische en numerieke gegevens over wegdekken, productie- en opslagcapaciteiten en kosten. De tweede fase richtte zich op het begrijpen van de bestaande patronen in de asfaltketen door middel van een literatuurstudie en interviews met belangrijke belanghebbenden, waarbij de huidige dynamiek en uitdagingen in de toevoerketen werden onthuld. De derde en laatste fase draaide om het ontwikkelen van een Mixed Integer Linear Programming (MILP) model om scenario's voor de asfaltketen met en zonder asfaltbank in specifieke perioden te simuleren en te vergelijken, waarbij de economische en logistieke impact werd beoordeeld.

De resultaten laten zien dat de introductie van een asfaltbank de totale kosten van de asfaltketen met €10,961,926 (27.0%) verhoogt, voornamelijk door hogere transport-, verwerkings-, grondstofkosten en extra kosten voor de asfaltbank en voorbewerking van asfaltgranulaat. In tegenstelling tot de aanvankelijke verwachtingen toonde het model aan dat het scenario met de asfaltbank leidt tot lagere asfalt recyclingpercentages en een hoger gebruik van primaire grondstoffen om de totale kosten van de asfaltketen te minimaliseren. Dit komt doordat de kostenbesparingen door verminderd primair grondstoffengebruik en lagere kosten voor de asfaltbank voorbij een bepaald niveau van asfalt hergebruik worden overtroffen door de toenemende kosten voor transport, verwerking en voorbewerking van het benodigde asfaltgranulaat. Desondanks kan de gecentraliseerde opslag van asfaltgranulaat door de asfaltbank de logistiek optimaliseren en mogelijk de CO_2-uitstoot verminderen door minder transport, mits meerdere asfaltbanken strategisch binnen de Vervoerregio Amsterdam worden geplaatst.

De bevindingen suggereren dat, hoewel een regionale asfaltbank de materiaalstroom van asfaltgranulaat aanzienlijk zou veranderen door de gefragmenteerde asfaltketen om te vormen tot een meer gecentraliseerd systeem en de opslag van asfaltgranulaat binnen de Vervoerregio Amsterdam te optimaliseren, dit niet noodzakelijk leidt tot hogere recyclingpercentages of lagere totale kosten. De kostenstijging en de complexe wisselwerking tussen het gebruik van primaire grondstoffen en recyclingpercentages benadrukken echter de noodzaak voor een uitgebreidere analyse, waarbij rekening wordt gehouden met factoren uit de praktijk, zoals opslagcapaciteitsbeperkingen en aanbestedingspraktijken.

Summary

This Master's Thesis studies the potential impact of implementing a regional asphalt bank on the spatial and temporal dynamics of Reclaimed Asphalt Pavement (RAP) within the Amsterdam Transport Region. It contributes to the Dutch asphalt sector's sustainability goals set out by Rijkswaterstaat in response to the climate objectives of the Dutch government and the Paris Climate Agreement. The study addresses the challenges in RAP recycling, particularly the difficulties of increasing recycling rates in asphalt surface layers, exploring how an asphalt bank might influence RAP's spatial and temporal distribution.

The research was conducted in three phases: inventory, analysis, and modelling. The first phase involved collecting and analysing data on the current road network and asphalt supply chain, including geographical, geometrical, and numerical data on road surfaces, production and storage capacities, and costs. The second phase focused on understanding the existing patterns in the asphalt supply chain through a literature review and interviews with key stakeholders, revealing the current dynamics and challenges in the supply chain. The third and final phase revolved around developing the Mixed Integer Linear Programming (MILP) model to simulate and compare asphalt supply chain scenarios with and without an asphalt bank in particular periods, assessing its economic and logistical impacts.

The results show that introducing an asphalt bank increases the total supply chain cost by €10,961,926 (27.0%), primarily due to higher transport, handling, raw material expenses, and additional asphalt bank and RAP processing costs. Contrary to initial expectations, the model showed that the asphalt bank scenario results in lower RAP recycling rates and higher raw material use to minimise the total supply chain costs. That is because, beyond a certain level of RAP reuse, the cost savings from reducing raw material and asphalt bank expenses are outweighed by the increased costs associated with transporting, handling, and pre-processing the required RAP material. Nevertheless, the centralised storage of RAP by the asphalt bank could optimise logistics and potentially reduce CO_2 emissions because of reduced transport if multiple asphalt banks were strategically located within the Amsterdam Transport Region.

The findings suggest that while a regional asphalt bank would significantly alter RAP material flow by transforming the fragmented supply chain into a more centralised system and optimising RAP storage within the Amsterdam Transport Region, it does not necessarily enhance recycling rates or reduce overall costs. Nevertheless, the cost increase and the complex interplay between raw material use and recycling rates highlight the need for a more comprehensive analysis, including considering real-world factors such as storage capacity constraints and tendering practices.

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Glossary

Term	Definition & Explanation
Reclaimed Asphalt Pavement (RAP) material	Reclaimed Asphalt Pavement (RAP) material is milled asphalt applicable for reuse in new asphalt mixtures. Other names might be milled asphalt or asphalt granulate.
Asphalt bank	The asphalt bank is a central facility for (temporary) storage of Reclaimed Asphalt Pavement (RAP) material.
Asphalt market dynamics	Asphalt market dynamics is an umbrella term for four dynamic factors of the asphalt market for Reclaimed Asphalt Pavement (RAP) material of interest to this study. These dynamic factors are. (1) The acquisition of RAP material, (2) the production capacity and storage infrastructure, (3) the distribution logistics, and (4) the market demand and pipeline projects.
In-use asphalt mixture stock	In-use asphalt mixtures stock is the stock of asphalt in a road currently in use, which will be available for reuse if released in the future.
RAP material stock	RAP material stock is a stockpile of milled asphalt, generally stored at a storage facility or an asphalt plant.
Mixed-Integer Linear Programming (MILP) model	A Mixed-Integer Linear Programming (MILP) model is a mathematical optimisation approach involving continuous and integer decision variables. It aims to optimise a linear objective function subject to linear constraints, where some variables are restricted to integer values. MILP is widely used in logistics, finance, and engineering to solve complex decision-making problems.
SQL Database	An SQL Database is a data structure managed and queried using Structured Query Language (SQL). It organises data into tables with rows and columns, allowing for efficient storage, retrieval, and manipulation of information. SQL databases are widely used for managing data in applications.

1 Introduction

This chapter introduces the problem context and outlines the study's problem statement, objective, and research questions.

1.1 Problem Context

The Dutch asphalt sector is increasingly focusing on sustainable practices, driven by the goal set by Rijkswaterstaat (the Dutch directorate-general for public works and water management) to achieve a climate-neutral asphalt sector by 2050 [1]. Among the initiatives to meet this objective, increasing and enhancing the reuse of Reclaimed Asphalt Pavement (RAP) is considered to hold significant potential. Although RAP is currently being recycled, challenges persist in incorporating it in high amounts into surface layers, limiting the efficiency of its reuse. One promising development to address these challenges is the concept of an asphalt bank [2].

An asphalt bank acts as an intermediary facility that manages the collection, pre-processing, storage, and redistribution of RAP rather than directly transporting RAP to individual asphalt plants. In the current asphalt supply chain, asphalt plants directly collect RAP from road maintenance locations; an asphalt bank, however, would centralise and optimise this process by pre-processing the RAP, ensuring better control over the quality and availability of RAP. The envisioned benefits include the production of higher-quality RAP reusable at larger percentages in new asphalt mixtures, as well as better regulation of material distribution to address shortages and surpluses at a regional level [3] [4]. However, the impact of such a third-party entity as an asphalt bank on the regional distribution of RAP and its financial viability remains uncertain, representing a gap in the current literature [5].

This study specifically aims to determine the effect of an asphalt bank on the spatial and temporal dynamics of RAP within the Amsterdam Transport Region in the Netherlands. To achieve this, a Mixed Integer Linear Programming (MILP) model, a mathematical model representing the asphalt supply chain within the Amsterdam Transport Region, has been developed to simulate and analyse the potential impact of an asphalt bank. The research involved an extensive data collection process encompassing geographical, geometrical, and numerical analyses of the local road network, asphalt plants, and other key asphalt supply chain components, providing a robust foundation for the model.

The structure of this thesis is organised to systematically address the research questions and objectives. The following chapters cover the literature review, theoretical framework, methodology, regional road network analysis, patterns of the current asphalt market, the modelling of the asphalt bank, the results from the model simulations, and the implications of these findings. Each chapter builds on the previous one, culminating in a comprehensive analysis of the potential role of a regional asphalt bank in optimising RAP usage and contributing to a more sustainable asphalt industry.

1.2 Problem Statement

The use of RAP in asphalt production is a critical strategy for achieving circularity and advancing environmental sustainability in road Construction. RAP reuse helps reduce the demand for primary materials, lowers CO_2 emissions, and contributes to resource efficiency. However, despite its potential, there are significant challenges in effectively utilising RAP within the asphalt supply chain, particularly when considering temporal and spatial dynamics.

The literature on the environmental and economic benefits of RAP does not adequately consider the constraints associated with its use, such as:

1. The temporal and spatial availability of RAP;
2. The production and storage capacity limitations of existing asphalt plants;
3. And the fluctuating demand for new asphalt mixtures over time and at the road network level.

These constraints can lead to inefficiencies in RAP management, including an uneven supply of materials, limiting storage capabilities, and challenges in aligning RAP availability with demand, ultimately impacting sustainability outcomes and cost-effectiveness. Additionally, while material hubs have been proposed in other industries to close material loops and enhance the intake of recycled or recovered materials, their application in the asphalt supply chain - particularly in the form of a regional asphalt bank - has not been explored. This study addresses these gaps by developing a MILP model to simulate the impact of a regional asphalt bank on the spatial and temporal dynamics of RAP. The model will optimise supply chain efficiency while considering the constraints related to RAP availability, asphalt plant capacity, and demand fluctuations. Through this approach, the study will evaluate the asphalt bank's environmental and economic benefits, providing a foundation for assessing its viability as a sustainable solution for RAP management in the Amsterdam Transport Region. The findings could also inform RAP management practices in other urban areas aiming to achieve circularity in construction materials.

1.3 Research Objective

Based on the problem statement, this research aims to investigate the economic and physical impact of implementing a regional asphalt bank on the spatial and temporal dynamics of Reclaimed Asphalt Pavement (RAP) within the Amsterdam Transport Region's asphalt supply chain.

1.4 Research Questions

To fulfil the research objective, the following research question and sub-questions need to be answered:

What is the impact of a regional asphalt bank on the RAP material stock in the Amsterdam Transport Region and asphalt supply chain costs?

To support the main research question, a set of sub-questions are formulated:

1. How is in-use asphalt mixture stock, potentially released within the next five years, geographically distributed in the current road network of the Amsterdam Transport Region?
2. What are the asphalt market dynamics of RAP material considering the four asphalt plants in the Amsterdam Transport Region?
3. What are the effects of a regional asphalt bank on the RAP material stocks at the four asphalt plants and the spatial distribution in the Amsterdam Transport Region over time?

2 Literature Review

This chapter reviews the literature on sustainable practices in the asphalt industry, focusing on using Reclaimed Asphalt Pavement (RAP) as a key component in promoting circular economy principles. The chapter highlights RAP's environmental and economic benefits and discusses the challenges of ensuring high-quality asphalt surface layers and overcoming logistical barriers. It explores various strategies for improving recycling management and examines how Material Flow Analysis (MFA) and supply chain optimisation methods can enhance recycling efforts and drive sustainability in the sector. Finally, the chapter identifies the research gap and introduces the study's contribution to addressing these challenges.

2.1 Introduction to Sustainable Practices in the Asphalt Sector

Globally, the asphalt industry is adopting more sustainable practices, driven by the need to reduce environmental impact and promote circularity. RAP plays a key role in this shift by reducing the demand for raw materials and lowering CO_2 emissions [6]. However, challenges remain, particularly in recycling RAP into surface layers without compromising performance [7].

In the Netherlands, Rijkswaterstaat has set a target for a climate-neutral asphalt sector by 2050. Their roadmap emphasises maximising RAP usage and minimising the need for raw materials. Innovations like asphalt banks could centralise and improve RAP management, enhancing recycling rates and supply chain efficiency. These efforts aim to position the Dutch road construction sector as a leader in sustainable asphalt production [1].

2.2 The Role and Challenges of RAP in Asphalt Production

RAP is integral to the circular economy in road construction, offering significant environmental and economic benefits. By reducing the demand for raw materials like aggregates and bitumen, RAP helps lower CO_2 emissions and promotes resource efficiency, making it a key component in sustainable asphalt production [5] [8]. The reuse of RAP aligns with Circular Economy (CE) principles, supporting closed-loop systems that minimise waste and conserve raw materials.

Despite these advantages, the full potential of RAP remains underutilised due to several challenges. One of the main obstacles is ensuring consistent material quality, especially when using higher percentages of RAP in surface layers, where performance standards are more stringent. Additionally, limited recycling capacity, storage constraints, and logistical issues hinder the efficient management of RAP [2] [5]. Although RAP is used in asphalt mixtures in the Netherlands, its application in high-performance surface layers is still limited, indicating a gap in fully achieving the sustainability goals outlined by Rijkswaterstaat [4].

2.3 Material Flow Analysis (MFA) in Circular Economy Systems

MFA is a key method for assessing the movement and stock of materials within a defined system, making it an essential tool in circular economy research. By systematically tracking the flow of materials, MFA enables better resource management and highlights opportunities for improving sustainability [9]. In the context of the asphalt sector, MFA can help assess the flow of RAP through the supply chain, providing insights into material reuse and resource efficiency.

MFA has been used widely across various sectors. For instance, Li et al. (2021) conducted an MFA of aluminium in China, tracking its lifecycle stages to identify potential efficiency gains [10]. Similarly, Westbroek et al. (2021) mapped the global glass supply chain, focusing on emissions reduction opportunities [11]. These studies exemplify how MFA can provide valuable insights into material flows and their environmental impact.

Grossegger's (2022) study on the anthropogenic flow of asphalt in an Austrian municipality provides a relevant case. It comprehensively analysed the flow of asphalt, identifying recycling amounts and material losses, which can be compared to the challenges faced in urban regions like the Amsterdam Transport Region [8]. Such research underscores the need for a deeper understanding of RAP flows to enhance recycling efforts and meet sustainability goals.

2.4 Circular Economy and Asphalt Supply Chain Management

The principles of the Circular Economy (CE) are central to achieving sustainability in the construction industry, where the focus is on minimising waste and maximising the reuse and recycling of materials. In the asphalt sector, this approach is vital for reducing the consumption of raw materials and enhancing resource efficiency through the reuse of RAP. [6].

Within the asphalt industry, there is increasing recognition of the need to adopt circular practices. Studies such as Mantalovas & Di Mino (2019) have emphasised that a circular economy model for asphalt can significantly enhance the reuse of RAP. One of the key innovations in this regard is the concept of a reclaimed asphalt processing plant (asphalt bank), which acts as a centralised facility for processing and storing RAP, thus optimising its reuse in new asphalt mixtures [6]. By centralising these processes, asphalt banks help manage the flow of recycled materials, reducing inefficiencies in the current supply chain where RAP is delivered directly to asphalt plants.

Shahsavani & Goli (2023) further explore the role of recycling facilities within the CE framework. They propose that by centralised processing and redistribution, recycling facilities, such as an asphalt bank, can improve the consistency and quality of recycled materials, reduce the demand for new materials, and lower emissions. This collaborative approach also encourages the development of best practices and innovative technologies, making asphalt banks a pivotal innovation for advancing CE principles in the asphalt industry [7].

2.5 Spatial Distribution and Supply Chain Optimisation in Recycling Networks

Optimising material flows within recycling networks is crucial for improving the efficiency and sustainability of circular supply chains. One of the primary methods for achieving this is through Mixed-Integer Linear Programming (MILP), which has been applied widely in various material recycling contexts. For example, Santander et al. (2020) used MILP to design a closed-loop supply chain for plastic waste in France, optimising the network by minimising transportation, processing, and facility operation costs [12]. Similarly, Komkova & Harbert (2023) applied MILP to the recycling of building materials such as concrete and mineral wool, highlighting the adaptability of MILP for different materials [13].

Tsydenova et al. (2021) presented a bi-objective MILP model for optimising concrete recycling networks. This approach focused on cost minimisation and promoting circular economy goals by reducing the reliance on natural aggregates and prioritising recycled material use. This dual focus on economics and sustainability is particularly relevant to managing reclaimed materials in other sectors, including asphalt [14].

Applying MILP to the asphalt sector, specifically for optimising the RAP supply chain, presents similar opportunities and challenges. For example, Tsui et al. (2024) developed a spatial optimisation model for timber hubs in the Amsterdam Metropolitan Area. Their model aimed to balance cost efficiency with environmental benefits by optimising the number and location of hubs to reduce transport distances and match the supply and demand for recycled timber. These insights into spatial optimisation could inform strategies for efficient RAP management in urban regions where centralised asphalt banks may play a key role [15].

2.6 Research Gap and Contribution

The existing literature has made significant strides in understanding the benefits of RAP in achieving circularity within the road construction sector. However, there remains a critical gap concerning the spatial and temporal dynamics of RAP. While studies have explored the theoretical frameworks of CE and MFA, they often fail to address the practical challenges of real-time RAP management and geographical mismatches between RAP supply and demand [5]. Additionally, the potential role of a centralised facility like an asphalt bank in optimising these material flows has not been investigated thoroughly.

This research aims to fill this gap by developing a MILP model that simulates the impact of an asphalt bank on RAP supply chain dynamics. By incorporating spatial and temporal considerations, the study will provide a more accurate representation of how a centralised facility could enhance RAP utilisation, streamline material flow, and reduce inefficiencies. The findings will offer practical insights for improving RAP management in urban settings, supporting sustainable asphalt production, and potentially informing similar strategies in other cities.

This contribution will advance theoretical discussions around circularity in the asphalt sector and offer tangible solutions to the logistical challenges of RAP recycling, driving the sector closer to its sustainability goals.

3 Theoretical Framework

The concepts of *Material Flow Analysis (MFA)*, *Circular Economy (CE)*, and *Spatial Distribution Modelling* play a significant role in this research. They are, therefore, the core concepts defined in the theoretical framework. A connection is made between these concepts to understand how a regional asphalt bank can influence the overall management and utilisation of RAP material, thereby enhancing sustainability and efficiency in asphalt production, road maintenance and construction projects. In short, the asphalt supply chain.

3.1 Material Flow Analysis

Material Flow Analysis (MFA) systematically assesses the flows and stocks of materials within a system defined in space and time. In the context of RAP material, MFA facilitates the tracking and analysing of asphalt materials throughout their lifecycle, from extraction through various end-of-life stages, including recycling and disposal.

Historically, MFA has been used to track and analyse a wide range of materials. For example, Li et al. (2021) investigated the material flows of aluminium in China across different lifecycle stages [10]. Westbroek et al. (2021) mapped the global glass supply chain to identify emissions reduction opportunities [11]. A closely related study by Grossegger (2022) investigated the anthropogenic flows and stocks of asphalt in the road network of an Austrian municipality [8]. This study is a relevant comparison as it provides a comprehensive MFA of the asphalt supply chain within an Austrian municipality, including detailed information on potential recycling amounts and material losses.

Basic Steps of a Material Flow Analysis

The studies referenced typically adhere to four fundamental steps in their MFA (Figure 3.1):

1. **Data Collection**: Gathering information on the quantities and qualities of materials at various life cycle stages.
2. **System Definition**: Establishing the boundaries for the analysis.
3. **Material Flow Mapping**: Outlining the stocks and flows within the defined system.
4. **Analysis**: Evaluating the efficiency and sustainability of current practices, identifying bottlenecks or inefficiencies, and assessing the potential impact of interventions.

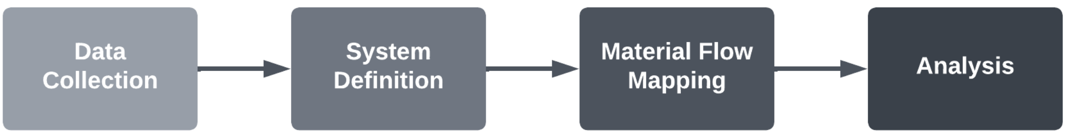

Figure 3.1: The Four Basic Steps of a Material Flow Analysis.

This study uses an MFA to understand how RAP material is used and reused within the asphalt supply chain in the Amsterdam Transport Region. While MFA is a crucial background tool, the primary aim is to develop a mathematical model that simulates these material flows. This model will offer insights into the spatial and temporal distribution of RAP, recycling rates, and the potential advantages of centralised RAP management through a regional asphalt bank. By adopting this approach, the study aims to provide insight into sustainable management and utilisation of asphalt materials in Amsterdam, aligning with circular economy (CE) principles that emphasise material reuse and recycling to establish closed-loop systems, thereby minimising waste and resource consumption.

3.2 Circular Economy

The Circular Economy (CE) concept is fundamental for understanding how a regional asphalt bank can enhance the sustainability and efficiency of asphalt production, road maintenance, and construction. CE is an economic system designed to eliminate waste and promote the continual use of resources through recycling, reuse, remanufacturing, and refurbishing, thereby creating a closed-loop system [7]. Although recycling asphalt and circular material flows has been common in the Dutch road construction sector for some time, further improvements are necessary for fully implementing the CE principles.

The study by Mantalovas & Di Mino (2019) illustrates a progressive step in the current circular system by incorporating a Reclaimed Asphalt (RA) processing plant/storage, akin to a central RAP management system or asphalt bank [6]. Shahsavani & Goli (2023) highlight the impact of CE principles on the lifecycle of asphalt materials, stating that a regional asphalt bank can (1) reduce the demand for new materials, (2) minimise waste, and (3) lower emissions, aligning with CE goals to maximise material use and value [7].

Circular Economy (CE) System

The CE system proposed by Mantalovas & Di Mino (2019) serves as the foundation for this study (Figure 3.2). The integration of an asphalt bank – equivalent to an RA processing plant – differentiates this updated model from the current system, where RAP material is sent directly to asphalt plants. According to Shahsavani & Goli (2023), incorporating an asphalt bank based on CE principles is expected to improve RAP management efficiency and sustainability through [7]:

1. **Centralised RAP Processing and Storage**: Streamlining the recycling process ensures consistent quality and availability of reclaimed asphalt.
2. **Facilitating RAP Exchange**: Enabling the exchange of RAP between different stakeholders, optimising the use of available RAP, and reducing the need for new materials.
3. **Promoting Collaborative Efforts**: Encouraging cooperation among stakeholders to develop best practices for RAP management and innovative recycling technologies.

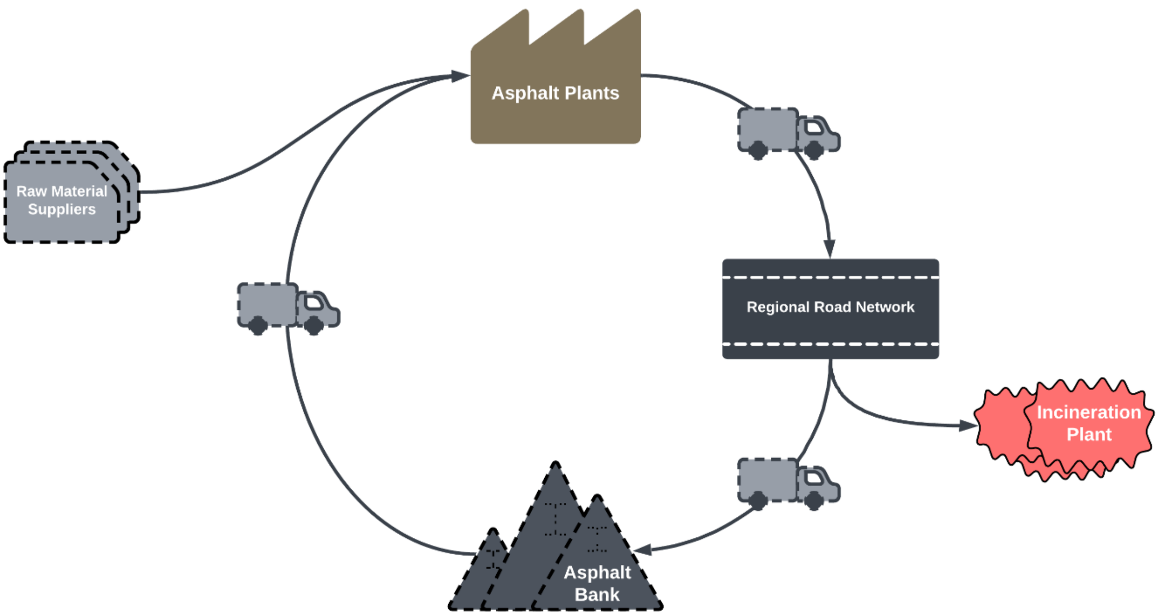

Figure 3.2: Circular Economy System Asphalt Supply Chain.

By integrating CE principles with a regional asphalt bank, the Amsterdam Transport Region can enhance RAP material management, laying the groundwork for developing a mathematical model of the asphalt supply chain that simulates material flows within this CE framework.

3.3 Spatial Distribution Modelling

Spatial Distribution Modelling is pivotal for optimising supply chain networks, particularly in recycling and CE initiatives. Mixed-integer Linear Programming (MILP) is one effective methodology employed in this domain. MILP models optimise the spatial distribution of recycling networks for various materials and scales. This section highlights key findings and methods from previous research.

Santander et al. (2020) explored closed-loop supply chain networks for plastic waste around Metz, France, utilising MILP to identify optimal configurations of distributed recycling networks while minimising costs associated with transport, processing, and facility operation [12]. Similarly, Komkova & Habert (2023) optimised supply chain networks for building material waste in Switzerland [13].

Tsydenova et al. (2021) applied a bi-objective MILP model to optimise concrete recycling networks, focusing on minimising costs and enhancing circularity by substituting primary natural aggregates with recycled concrete aggregates [14]. Another relevant study by Tsui et al. (2024) used spatial optimisation techniques to establish circular timber hubs, closely aligning with this research's aim to optimise the location and efficiency of asphalt banks [15].

Spatial Distribution Modelling using a MILP Model

The reviewed literature underscores the application of MILP for spatial distribution problems, guiding the methodology for this research. MILP models typically consist of three components (Figure 3.3):

1. **Decision Variables**: Represent the continuous or binary choices the model can make.
2. **Objective Function**: Representing the goal of the model, which is most often minimising costs or environmental impact (CO2 emissions).
3. **Constraints**: Define the mathematical relationship between the different decision variables and parameters. There are boundaries placed on the values of the decision variables.

Figure 3.3 illustrates the components of a MILP model. The solutions that optimise the objective functions are computed by using a mathematical solver.

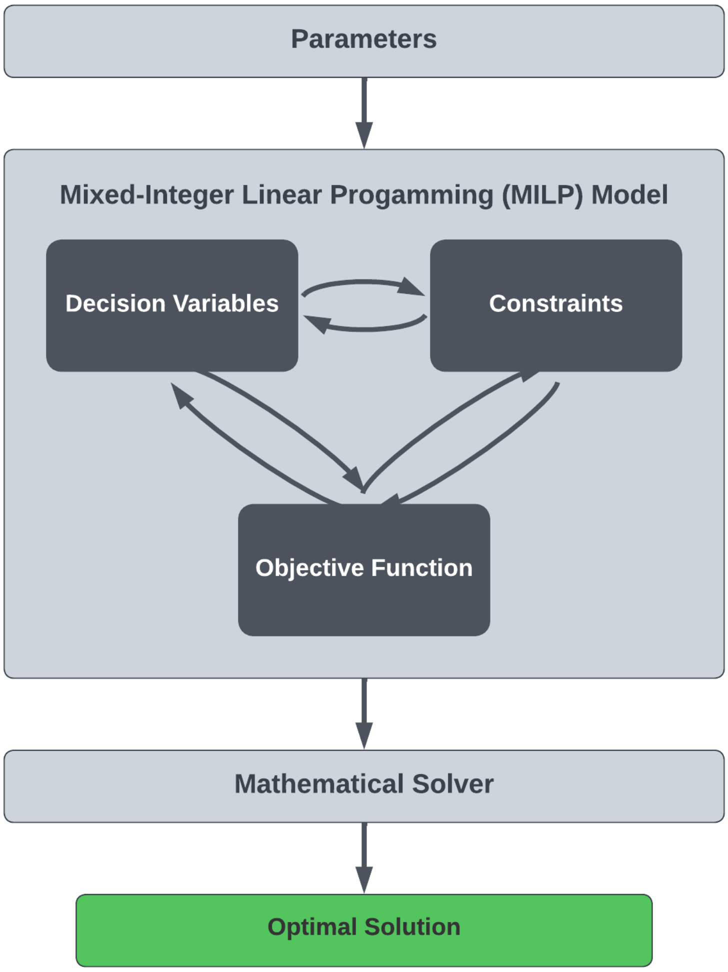

Figure 3.3: Basic Setup and Components of a MILP Model.

MILP is particularly suited to this research due to its capacity to address the complexity of optimising the spatial and temporal dynamics of RAP materials while incorporating economic and technical constraints. Its adaptability across various scales and material types positions it as an ideal modelling choice for the RAP supply chain in the Amsterdam Transport Region.

3.4 Conclusion of Theoretical Framework

In summary, this theoretical framework integrates Material Flow Analysis, Circular Economy principles, and Spatial and Temporal Distribution Modelling to address the central research question regarding the impact of a regional asphalt bank on RAP material stocks in the Amsterdam Transport Region. These three concepts converge within the Mixed-Integer Linear Programming (MILP) model, which serves as the foundation of this research. The CE framework is mathematically defined within this model, enabling simulations that generate various material flows analysed through MFA. This integrated approach aims to develop a comprehensive model for managing RAP materials, enhancing material efficiency, and hopefully reducing environmental impacts within the asphalt supply chain.

4 Methodology

Three research phases are undertaken. (1) Inventory of the road network and physical asphalt supply chain; (2) analysis of patterns of the current asphalt supply chain; and (3) mathematical modelling of the asphalt supply chain. Each phase builds upon the previous one to comprehensively address the impact of an asphalt bank on the asphalt supply chain within the Amsterdam Transport Region. Figure 4.1 provides a schematic overview of these phases.

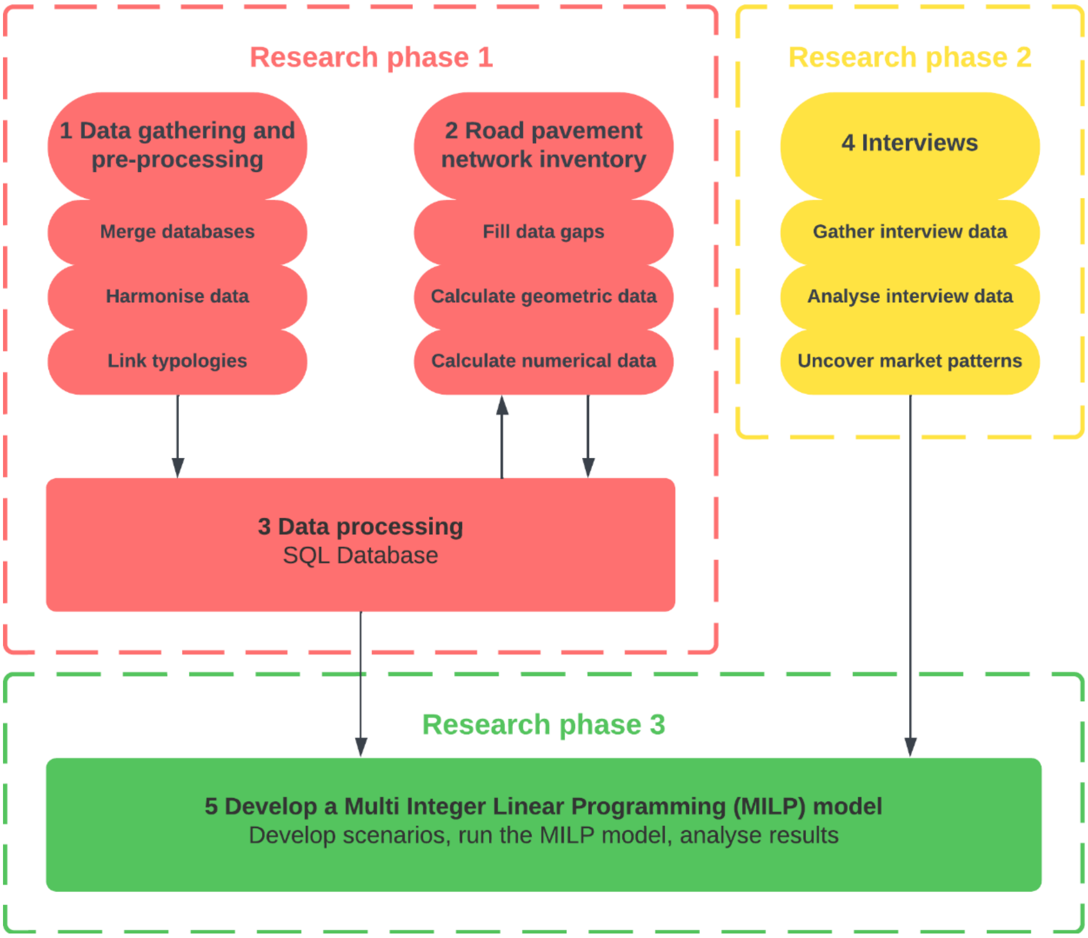

Figure 4.1: Overview Research Methodology.

Phase 1: Inventory of the Current Road Network and Asphalt Supply Chain

The first phase focuses on creating an inventory of the current road network and the asphalt supply chain within the Amsterdam Transport Region. The main objectives are to gather data on the quantity of asphalt present, the rate at which asphalt is released over time and space, and to identify the locations of the various parties involved in the asphalt supply chain. This foundational data will be input for the model developed in the third phase. The data collected includes geometrical data (e.g., road surface areas, volumes, supplier and asphalt plant locations) and numerical data (e.g., production capacity, storage capacities, asphalt lifespans, road topologies, and costs). Geospatial data will be sourced from Publieke Dienstverlening Op de Kaart (PDOK), while numerical data such as transport and land-use costs will be from the Dutch Central Bureau of Statistics and other sources.

Phase 2: Analysis of the Underlying Patterns in the Asphalt Supply Chain

The second phase aims to analyse the underlying patterns in the current asphalt supply chain within the Amsterdam Transport Region. That involves a detailed examination of practices and patterns in the asphalt market, forming a base scenario for the model in the third phase. Data collection in this phase includes literature and publications from CROW to support the supply chain analysis and interviews with key stakeholders, such as road managers, contractors, asphalt producers, and third parties. These interviews intend to gather practical insights into the asphalt supply chain that are not typically available in written literature. The interviews will provide information on the current dynamics regarding the storage and distribution of Reclaimed Asphalt Pavement (RAP) material, practices and challenges in the asphalt market, and factors influencing the road construction sector.

Phase 3: Modelling an Asphalt Bank and Its Effects on the Asphalt Supply Chain

The third phase focuses on modelling the location and operations of an asphalt bank and evaluating its effects on the supply chain. This phase uses data from the first two phases to create a realistic model scenario incorporating a (virtual) asphalt bank. The model aims to assess the impact of an asphalt bank on supply chain costs and optimise its location within the Amsterdam Transport Region. The asphalt bank scenario is based on the supply chain analysis and insights from the interviews, envisioning the bank as a facility that collects RAP and redistributes it to asphalt plants as needed. The model objective is to minimise total supply chain costs, allowing for a comparison between scenarios with and without an asphalt bank. The final analysis will provide insights into the model's performance and ultimately answer the main research question regarding the feasibility and impact of establishing an asphalt bank.

4.1 Data Collection

A mixed-method approach is employed to evaluate the impact of an asphalt bank on the asphalt supply chain, involving both literature review and interviews with relevant supply chain stakeholders. The data collection consists of two sources: literature sources (online & books) and interviews.

Literature and Online Sources

Literature and online sources serve as the primary information sources for model input data, analysis of the Amsterdam Transport Region, and general supply chain analysis. The data includes various formats such as scientific journals, book sections, geospatial data (Shapefiles), and numerical data (Excel). Geospatial data will be used to analyse the Amsterdam Transport Region and as input for the Mixed-Integer Linear Programming (MILP) model, focusing on road surfaces, suppliers and asphalt plant locations. Numerical data will cover production capacities, storage capacities, asphalt lifespans, road topologies, and costs. Sources for this data include PDOK, the Dutch Central Bureau of Statistics, and CROW publications.

Interviews

Interviews supplement the literature and online sources by providing practical insights into the asphalt supply chain, specifically those specific to the Amsterdam Transport Region. The interviews should yield data on current asphalt supply chain dynamics regarding the storage and distribution of RAP material, underlying market practices, and factors influencing the road construction sector. Stakeholders for the interviews include road managers, contractors, asphalt producers, and third parties (RAP pre-processing start-ups and wholesalers), with specific contacts such as Rijkswaterstaat, province of Noord-Holland, municipality of Amsterdam, Freesmij, Asfalt Recycle Bedrijf, ART Amsterdam, and Ballast Nedam.

4.2 Research Process

The research process is divided into three phases, each comprising specific steps.

Phase 1: Analysis of the Amsterdam Transport Region

The first phase involves two main parts: loading data and computing road surface areas and asphalt volumes. The loading data process includes researching, gathering, merging, and pre-cleaning geographical, geometrical and numerical datasets of the road network and supply chain stakeholders and storing them in an SQL database, forming the basis for the MILP model. That is based on the approaches of Miatto et al. (2017) [16] and Wang et al. (2023) [17]. The second part involves calculating the geometrical properties of the local road network to estimate road surface areas and volumes and determine the average lifespan of each road type to predict maintenance needs and potential RAP material releases over the next five years. This timeframe aligns with Rijkswaterstaat's climate targets for 2030, ensuring manageable computational times for the MILP model.

Phase 2: Patterns of the Current Asphalt Market

The second phase involves gathering and analysing interview data to uncover asphalt market patterns. The process includes planning, conducting, and transcribing interviews for four stakeholder groups: road authorities and managers, contractors and subcontractors, asphalt producers, and third parties. That was followed by a thematic analysis of the interview data to identify patterns in the reverse asphalt supply chain, specifically related to sustainability, recycling, and asphalt banks. This phase provides insights into current market dynamics, practices, and underlying patterns, contributing valuable information for the MILP model. For more information, see Appendix V – Interview Methodology.

Phase 3: Modelling the Asphalt Bank and the Effects on the Asphalt Market

The third phase revolves around developing the MILP model with and without an asphalt bank. The model aims to minimise total supply chain costs and compare the current situation with a scenario in which an asphalt bank is located in the region under study. The final analysis will demonstrate the model's outcomes, providing a comprehensive answer to the research question and evaluating the potential benefits of an asphalt bank within the Amsterdam Transport Region.

4.3 Tools and Software

The tools required for this research include an SQL database, Python, and standard office software. The SQL database serves two primary functions: storing the necessary data and performing computations via a Python script inspired by the approach used by Heeren and Hellweg (2018) [18]. The SQL database facilitates the management and retrieval of large datasets required for the MILP model. Other tools utilised in this research are:

- **Microsoft Word**: For documentation and report writing.
- **Microsoft Excel**: For data organisation, preliminary analysis, and visualisation.
- **Audio Recorder (e.g., phone)**: To record the interviews to ensure accurate data capture.

The primary tool in this research will be the Python-MIP package, a collection of Python tools for modelling and solving MILPs. This package is used for its user-friendly syntax and high performance, ensuring efficient and accurate modelling [19].

4.4 Validity and Reliability

Ensuring the validity and reliability of the research involves addressing potential biases and errors in the research design, data collection, and analysis processes. This research faces several potential threats. Therefore, the means of minimising or mitigating these threats are:

- **Selection Bias**: To minimise selection bias, a diverse group of stakeholders within the asphalt supply chain, including road authorities, contractors, asphalt producers, and third parties, will be interviewed.
- **Observer Bias**: To mitigate observer bias, interview results and possibly wrongfully interpreted information will be reviewed by the interviewees.
- **Data Analysis Errors**: To mitigate errors from inexperience with particular data types and analysis methods, the researcher receives feedback from the research supervisors.
- **Modelling Errors**: To mitigate errors from inexperience with programming and modelling a Mixed-Integer Linear Program (MILP) model, the research supervisors support the researcher. Additionally, the Python-MIP package ensures model feasibility.

Reliability and validity concerns also extend to the data collection methods:

- **Document and Database Analysis**: The reliability of documents and datasets depends on their quality and accuracy. The researcher aims to use documents from reputable institutes, assuming those to be reliable despite not being updated annually; however, if this is not the case, source validity is checked through cross-validation or expert opinion.
- **Interviews**: The reliability of interviews depends on consistent data collection by the interviewer, which depends on experience. Interview validity is enhanced by featuring open-ended questions, allowing interviewees to share their experiences freely.

By implementing these measures, the research aims to maintain high standards of validity and reliability, ensuring that the findings are robust and trustworthy.

5 Road Network of the Amsterdam Transport Region

The area selected for obtaining a deeper understanding of the asphalt supply chain and the potential impact of an asphalt bank is the Amsterdam Transport Region. This chapter provides detailed information on the geographical scope, the rationale for selecting this region, and the crucial data extracted from roads and supply chain stakeholders within this scope. The chapter is organised as follows:

- **Paragraph 5.1 Geographical Scope** – Discuss the scope of the study.
- **Paragraph 5.2 Road Network Inventory** – Describes the road network considered in this research, its topology, and the ownership and management of these roads.
- **Paragraph 5.3 Supply Chain Stakeholders –** Explains the key supply chain stakeholders within the scope.
- **Paragraph 5.4 Shortcomings and Limitations** – Discuss the potential limitations and shortcomings of the inventory within the study area.
- **Paragraph 5.5 Conclusion** – Summarises the chapter.

5.1 Geographical Scope

The geographical scope of this research focuses on the Amsterdam Transport Region (Vervoerregio Amsterdam), located in the Dutch province of Noord-Holland. This region is an administrative partnership of 14 municipalities in the Amsterdam area, tasked with various regional traffic and transport responsibilities. Additionally, the Transport Region oversees the development and improvement of infrastructure for cars, public transport, and bicycles [20]. Figure 5.1 provides an overview of the Transport Region and its 14 municipalities. Appendix I – Maps Amsterdam Transport Region presents the full-size maps.

This area was chosen for several key reasons:

- **Established Boundaries:** The Amsterdam Transport Region is a well-defined and fixed area. Consisting of 14 municipalities with established geographical boundaries.
- **Diverse Road Network Management:** The road network within this region is managed by the three public clients in the Netherlands: Rijkswaterstaat, the province, and municipalities. This variety allows for a comprehensive analysis of different maintenance projects, road types, management methods, inspection techniques, maintenance strategies, implementation methods, and accepted reuse percentages in asphalt mixtures.
- **Competitive Asphalt Market:** The region hosts four of the 25 asphalt plants in the Netherlands. That is unusual given the typical large distances between asphalt plants throughout the country, except in regions like Amsterdam and Rotterdam. The presence of multiple plants within a compact area results in a competitive asphalt market similar to that of the entire country.
- **Innovative Recycling Efforts:** This region features the first asphalt bank in the Netherlands, Asfalt Recycle Bedrijf (ARB). ARB, a partnership between Graniet Import and several major road construction contractors, is pioneering the preprocessing of milled Porous Asphalt (PA) 16 for high-quality recycling. This initiative is in its early stages but represents an interesting development for this study, particularly for the interviews with the regional supply chain stakeholders.

In summary, the Amsterdam Transport Region was selected due to its well-defined boundaries, diverse road network (management), concentration of asphalt plants, and the innovative ARB initiative. These factors create a unique environment for modelling an asphalt bank and its effects on the asphalt supply chain, with the potential to scale findings to a provincial or national level, as it has significant similarities.

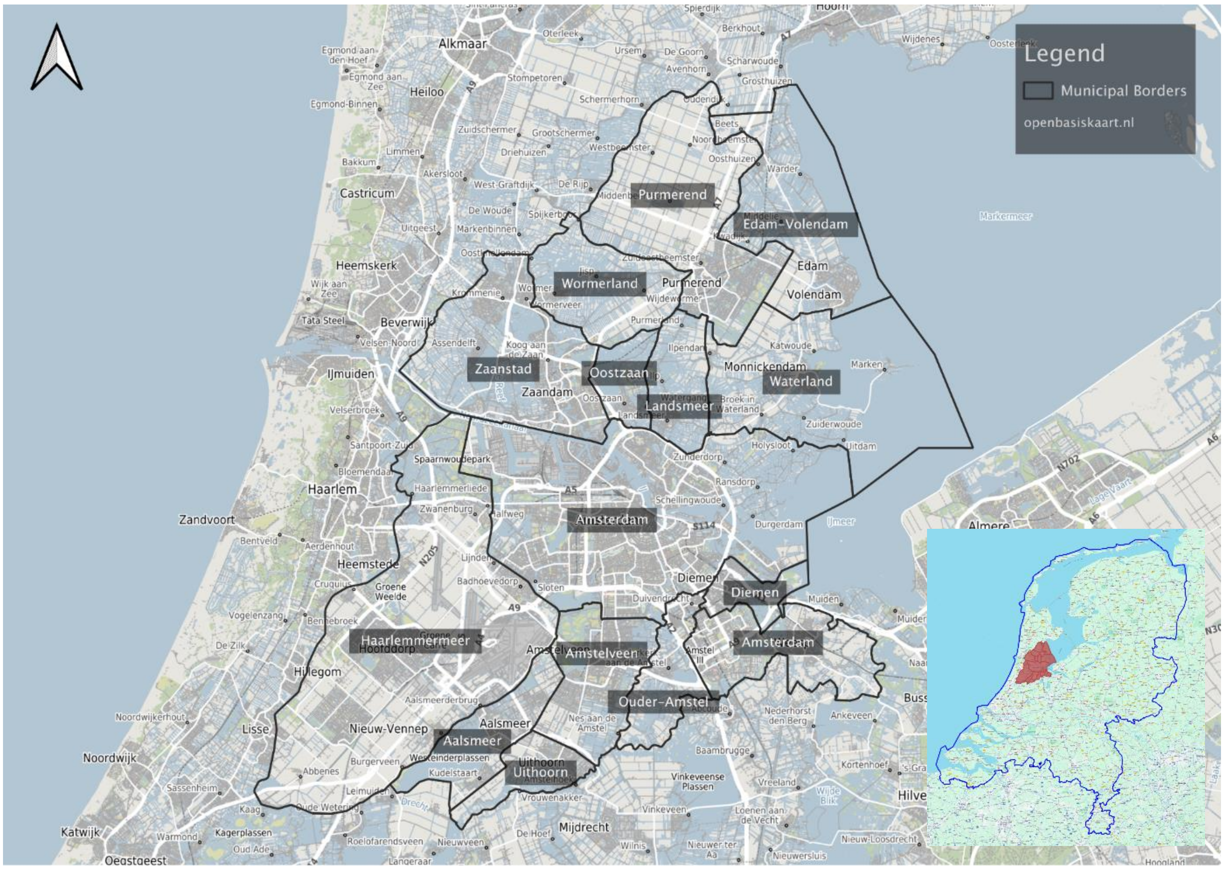

Figure 5.1: Overview of the Amsterdam Transport Region and its 14 Municipalities.

5.2 Road Network Inventory

The road network within the Amsterdam Transport Region is relevant to the developed model in this study. The road network is inventoried based on the Basic Registration of Large-Scale Topography (BGT), a highly detailed digital map of the Netherlands [21]. The BGT provides extensive details about the physical environment, including roads.

The BGT road section dataset includes 17 different road types, from cycle paths and equestrian trails to parking areas and airport runways. However, many of these roads have surfaces irrelevant to the asphalt supply chain, such as shells, tree bark, and baked pavers. This study focuses only on asphalt-paved roads; to select the relevant data, a Python script was developed to filter the original dataset. Appendix II – Coding Methodology Road Network provides a complete overview of the software, datasets, and Python script.

The script selects only road sections pertinent to this research, which include four variants that include the term roadways: local roads, regional roads, motorways, and freeways. This selection process excluded non-asphalt pavements, like cobblestone roads, while ensuring that significant stretches of freeway were not excluded due to missing values in the dataset. Only roads within the Amsterdam Transport Region are considered and grouped per participating municipality. Figure 5.2 presents the geographical data of this updated dataset, highlighting the relevant road network.

Various attributes, such as construction dates, functions, and source holders, are linked to this geographic data to utilise in the later research stages. The filtered road network dataset forms the foundation for the subsequent findings of this study. Figure 5.3 presents the individual road types existing in the Amsterdam Transport Region. For a comprehensive view, refer to Appendix I - Maps Amsterdam Transport Region, which includes full-size maps.

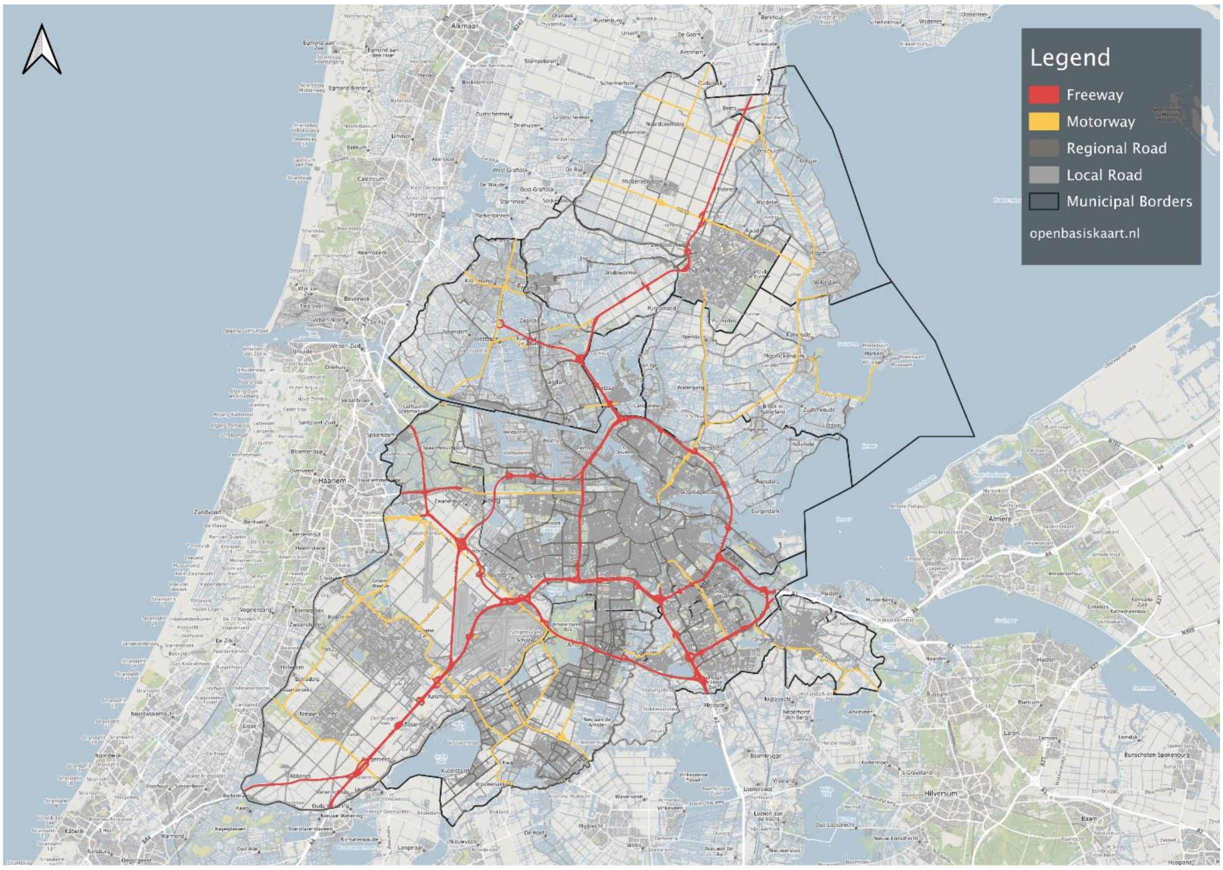

Figure 5.2: Relevant Road Network of the Amsterdam Transport Region.

The road network within the Amsterdam Transport Region - as illustrated in Figure 5.2 - covers a total area of 42.96 million m^2 (42.96 km^2). Given that the Amsterdam Transport Region has a total area of 948.19 km^2, 4.5% of the region's surface area is asphalt pavement. This 42.96 km^2 of asphalt pavement is subdivided as follows, as detailed in Figure 5.3:

- **Local Roads**: 27.10 km^2.
- **Regional Roads**: 5.84 km^2.
- **Motorways**: 3.01 km^2. One municipality, Landsmeer, does not have any motorways within its area.
- **Highways**: 7.02 km^2. Notably, three of the 14 municipalities (Aalsmeer, Uithoorn, and Waterland) do not have highways within their areas.

The following section delves into the road topology for these four road types and provides estimates of the volumes of different sorts of asphalt within the Amsterdam Transport Region. This detailed analysis aims to provide a comprehensive understanding of the road network's composition and asphalt distribution, laying the groundwork for the model development.

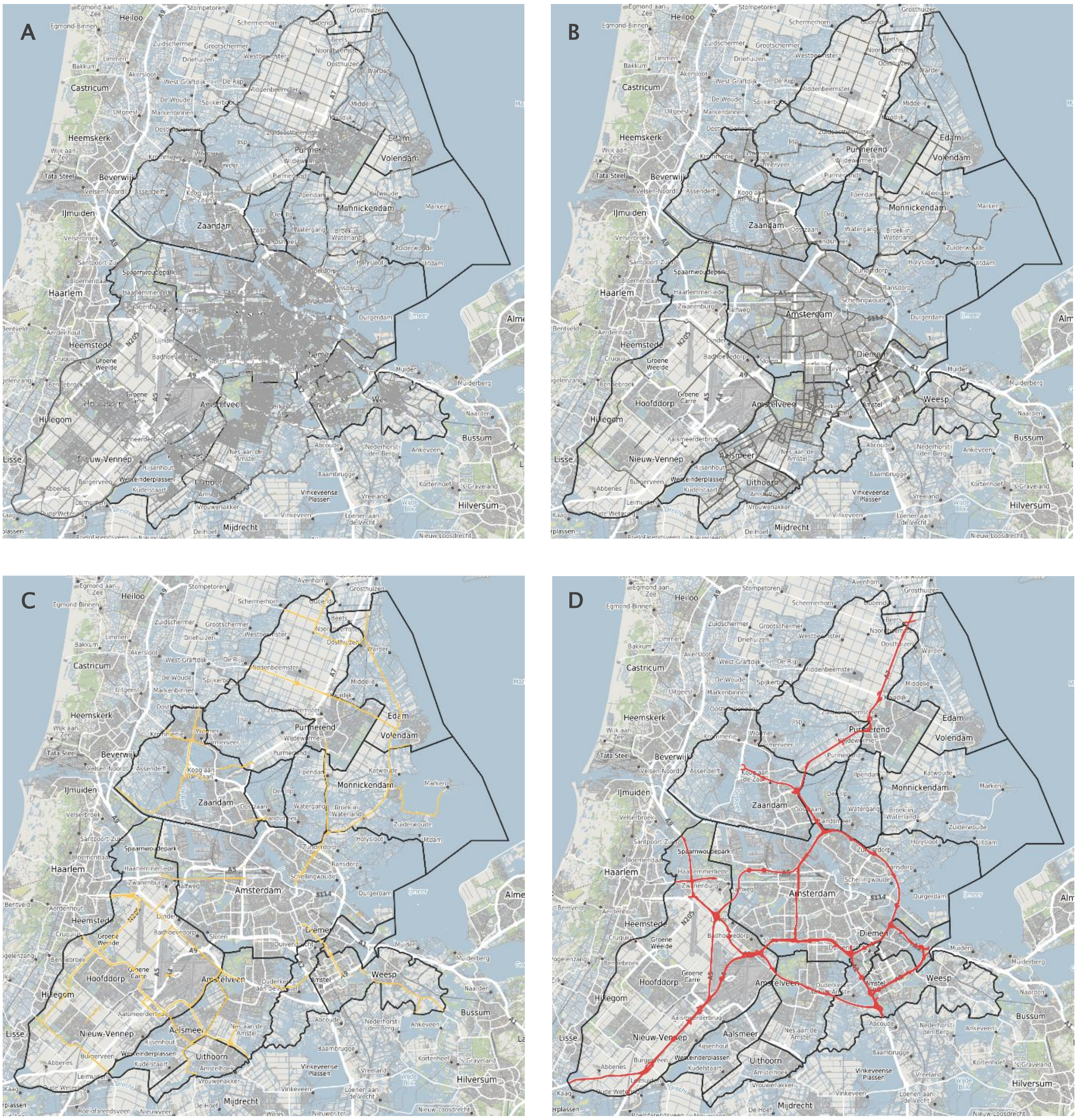

Figure 5.3: Local Roads (A), Regional Roads (B), Motorways (C), and Freeways (D) of the Amsterdam Transport Region.

5.2.1 Road Topology

With the road network mapped, understanding the structure of these roads is crucial for the subsequent phases of this study, particularly in developing the model. Each of the four different road types has a distinct standard road topology. These topologies are based on information in Appendix III – Road Topology Data [22], which contains detailed information on the standard road topologies.

Figure 5.4 illustrates the road topology data of a local road (A), regional road (B), motorway (C), and freeway (D) of this study, showcasing their complete structure. Typically, the motorway and freeway feature more significant amounts of asphalt. This research is limited to the asphalt layers, specifically down to and including the AC 22 Base layer.

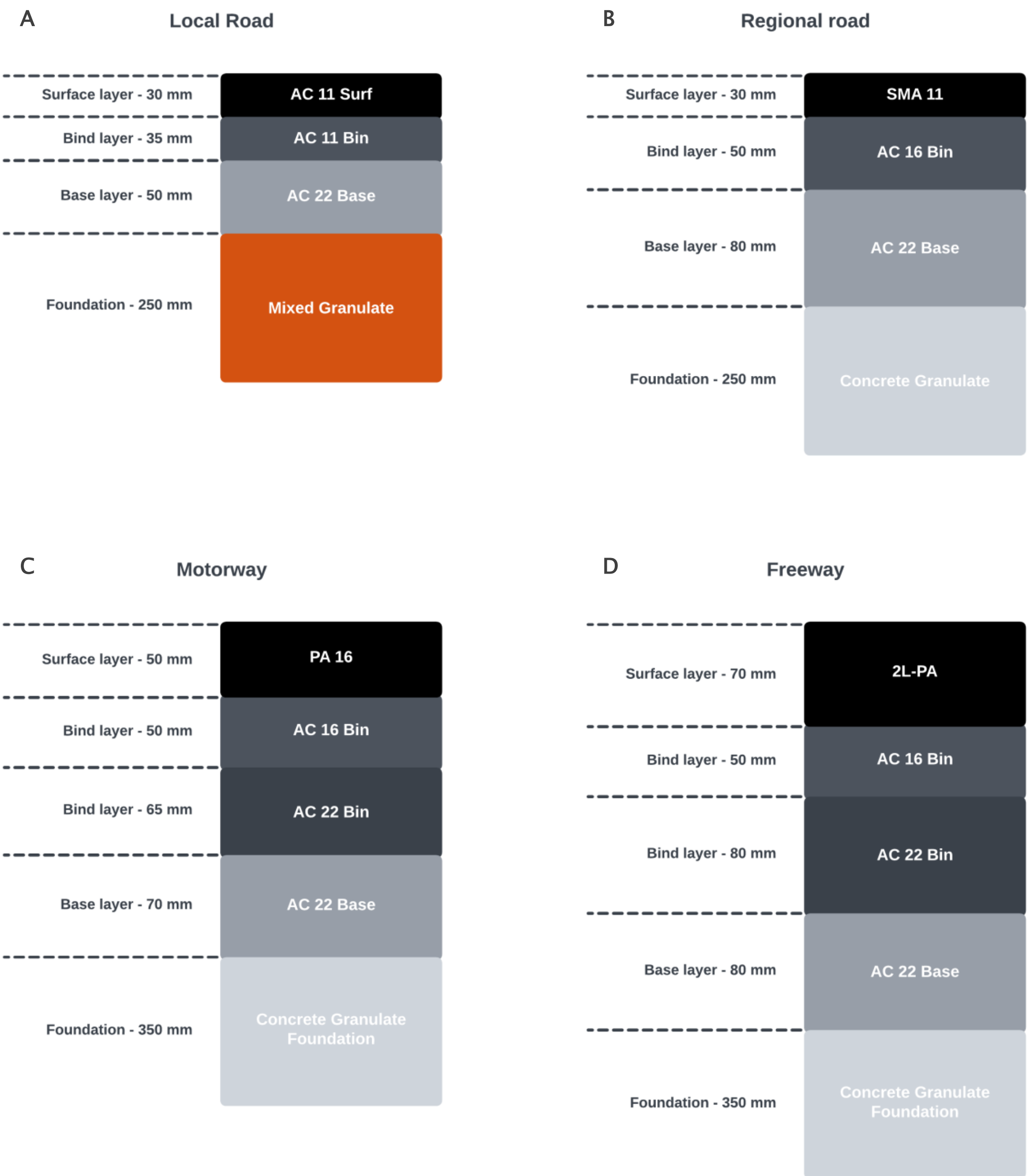

Figure 5.4: Road Topology of Local Road (A), Regional Road (B), Motorway (C), and Freeway (D).

Based on the road network and road topology shown in Figure 5.2 and Figure 5.4, respectively, the asphalt volumes in the road network are determined. Figure 5.5 presents the distribution of the asphalt volumes within the Amsterdam Transport Region. In this chart, the surface layers – those most suitable for high-quality reuse – are individually detailed, while the base and binder layers are combined.

The asphalt volume distribution for the Amsterdam Transport Region aligns closely with the EIB Report on Volume Balance of Asphalt Mixtures, particularly for the binder and base layers [3]. However, there are deviations in the surface layers, likely due to the differences in road topology used. Despite these variations, the values from the EIB Report and this study are relatively close, supporting the calculations made.

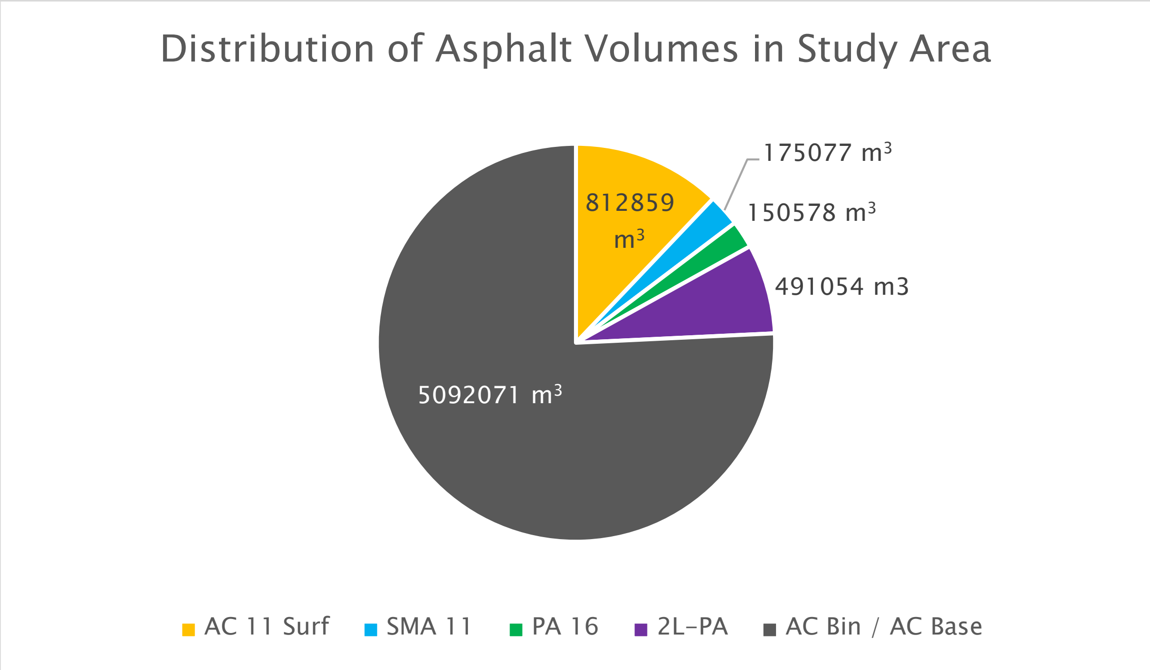

Figure 5.5: Pie Chart - Distribution of Asphalt Volumes in Study Area.

5.2.2 Ownership and Management

The road network under study is managed by three distinct government organisations: Rijkswaterstaat, the province of Noord-Holland, and the 14 municipalities that form the Amsterdam Transport Region. Each agency oversees a specific type of road and employs a maintenance approach that varies per organisation.

Rijkswaterstaat is responsible for the freeways, the thickest road structures and the most heavily loaded roads considered in this study. The province of Noord-Holland manages both motorways and regional roads. These roads serve as critical transitions between freeways and local roads. Finally, the 14 municipalities are each responsible for the local road network within their jurisdictions.

For this research, particularly for developing the model, it is essential to understand the average lifespan of these structures and the maintenance practices of each agency. The lifespan of asphalt pavement structures depends on multiple factors and variables, among which road topology and traffic loads; thus, the type and location of the road are the most significant as these two factors determine the amount of traffic load; in other words, road wear and consequently road maintenance.

On the other hand, the maintenance approaches significantly influence the amount of asphalt or RAP material available for reuse. For example, one organisation might remove and replace the surface and binder layers during major maintenance. In contrast, another organisation might only replace the surface layer, adding an extra binder layer on top of the old one. These differences significantly impact the material flows.

In summary, analysing the road network and its material flows requires considering the maintenance strategies of the road owners to assess the asphalt supply chain accurately. Insight from interviews with supply chain stakeholders on this matter is discussed in Chapter 6, Patterns of the Current Asphalt Market. Appendix VII – Interview Results provides detailed results and information on the maintenance practices of each government organisation.

5.3 Supply Chain Stakeholders

The previous section briefly discussed some of the asphalt supply chain stakeholders, specifically the road owners. However, numerous other parties are crucial for the eventual development of the model and for conducting interviews later in this research. These include raw material suppliers, asphalt plants, contractors, third parties, and road owners.

Only a select group of these parties and their locations are relevant for the operation of the supply chain, as shown in Figure 5.6. These include the supplier of coarse aggregates, Graniet Import, and the asphalt plants: Asfalt Productie Amsterdam (APA), Asfaltproductie Regio Amsterdam (ARA), AsfaltNu Amsterdam I (ANA I), and AsfaltNu Amsterdam II (ANA II). Additionally, the location of the Asfalt Recycle Bedrijf (ARB), a third party, is indicated. While the ARB's asphalt bank is not necessarily critical for the final model, it is significant for model testing and interviews. Government organisations and contractors are also relevant for the study; however, their locations are not fixed and thus excluded from the model.

The study area encompasses a sufficient number of parties to ensure a healthy competitive market, which is beneficial for the study's findings to have broad implications beyond the specific area under investigation.

In summary, Figure 5.6 highlights the locations of the raw material supplier, asphalt plants, and the ARB relevant to the model's development and operation. While not all stakeholders in the asphalt supply chain are shown, such as road owners and contractors, their working methods are essential for creating a realistic model. The study area is expected to represent a realistic, regional asphalt market due to the diverse composition of stakeholders involved.

For more detailed information about the asphalt supply chain stakeholders and interview insights, refer to Chapter 6, Patterns of the Current Asphalt Market.

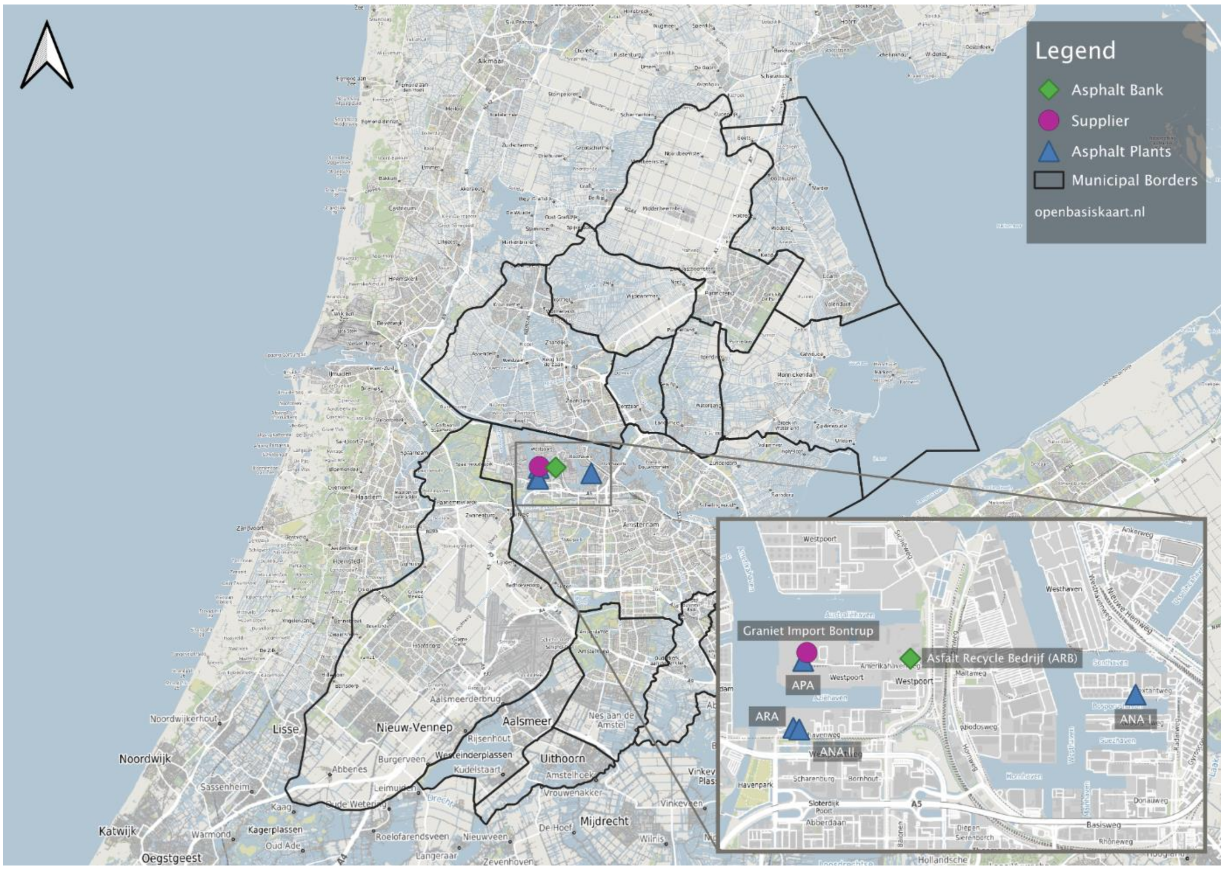

Figure 5.6: Supply Chain Stakeholders in the Amsterdam Transport Region.

5.4 Shortcomings and Limitations

This paragraph discusses the shortcomings and limitations of the methods applied to analyse and delineate the road network and asphalt supply chain in the Amsterdam Transport Region. Although there are limitations, all decisions were considered carefully with the purpose of the scope of this research in mind.

Data Accuracy and Completeness

One significant consideration is the accuracy of the data for analysing the road network. The source data is very precise, with a maximum deviation of 20 centimetres, which is more than sufficient for this study. However, it is not clear whether the data is complete, up-to-date, and entirely correct. Despite this, no discrepancies were discovered when compared with satellite date images from Google Maps. It was, therefore, assumed to be accurate.

Selective Road Type Analysis

This study only focuses on four of the 17 different road types in the dataset. The road types that do not consist of asphalt were excluded, but this selective approach also omitted significant volumes of asphalt, such as bicycle paths, parking lots, and airport runways. These exclusions were deliberate to avoid additional complexity and uncertainty. The selected roads account for the most significant volumes of asphalt relevant for high-quality reuse.

Material Property Filtering

The dataset attributes, including road surface material, are sometimes incomplete, stating "value-Unknown". Preventing the loss of relevant geographical information while filtering the dataset resulted in selecting roads with the attribute asphalt and also "valueUnknown" as a road surface material. Only selecting roads with the attribute asphalt would result in losing large stretches of freeway and other asphalt roads that lacked this attribute data. However, this may also inadvertently include some non-asphalt roads, such as cobblestone roads, lacking the road surface material attribute.

Standard Road Topology

The established road topology for the four road types is a generalised representation of the actual road structures. Despite the numerous variations in asphalt mixtures and designs, the standard road topology is relevant. Further variations due to maintenance are acknowledged, but more precise road topology data is not available and, in most cases, not fully known by road owners and managers.

Stakeholder Inventory and Analysis

Some stakeholders, like road owners and contractors, are considered in terms of their roles and methods, but their physical locations are not. Additionally, raw material suppliers of bitumen, fillers, and additives are completely excluded from the analyses to manage the model's complexity and focus on mapping primarily the RAP material flows and its alternative, the raw aggregate flows. Raw aggregates represent around 95% of an average asphalt mixture, with bitumen accounting for around 5%. The other material flows (additives) are considered neglectable for this research.

5.5 Conclusion

This chapter focuses on developing the geographical and geometrical information necessary for the model. Initially, the scope relevant to the entire study is defined and substantiated, followed by the distinction of the geographical and geometrical datasets. This scope is also pertinent to the interviews conducted later in the research.

The datasets, although not perfectly realistic, adequately represent the road network and asphalt supply chain in the Amsterdam Transport Region. While some non-asphalt roads might be included, the datasets considered are sufficiently realistic for simulating the asphalt supply chain and the impact of integrating an asphalt bank. The use of a standard road topology and a simplified supply chain does not significantly detract from the effectiveness of the simulation. Chapter 7: Modelling the Asphalt Bank and the Asphalt Supply Chain provided further information about the origin of the data used in the model.

In summary, this chapter investigates the physical elements within the research area. This inventory has led to the creation of several geographical and geometrical datasets used in the MILP model central to this study. Despite their shortcomings and limitations, based on visual inspection and comparison with existing literature, these datasets are deemed of sufficient quality and detail for their intended application in the developed model.

6 Patterns of the Current Asphalt Market

This chapter aims to provide a detailed analysis of the asphalt supply chain in the Netherlands, grounded in literature and more region-specific information about the reverse asphalt supply chain in the Amsterdam Transport Region through interviews. Additionally, practices focused on the reverse asphalt supply chain within the Amsterdam Transport Region are examined through interviews with multiple stakeholders. The analysis aims to offer theoretical and practical background information that will be the basis of the Mixed-Integer Linear Programming (MILP) model. This chapter is structured as follows:

- **Paragraph 6.1 Asphalt Supply Chain Analysis** – A brief overview of the asphalt supply chain, drawing on the extensive supply chain analysis.
- **Paragraph 6.2 Asphalt Market Stakeholder Interviews** – A summary of the main findings from the stakeholder interviews, highlighting agreements and disagreements among the groups within the Amsterdam Transport Region.
- **Paragraph 6.3 Thematic Analysis of the Interviews** – A brief exploration of the thematic analysis results from the interviews, presenting key similarities and contradictions among stakeholders and summarising key insights.
- **Paragraph 6.4 Conclusion** – A conclusion on the asphalt supply chain, integrating practical information gathered during the interviews.

6.1 Asphalt Supply Chain Analysis

The asphalt supply chain consists of a "forward" and "reverse" supply chain, forming together the closed-loop supply chain or circular asphalt market, presented in Figure 6.1. In this figure, the continuous arrows represent the forward supply chain or linear economy, and the dotted-lined arrows represent the reverse supply chain. The asphalt chain has four key stakeholders: raw material suppliers, asphalt plants, contractors, and clients. The processes range from supplying raw materials to using asphalt roads and road maintenance, ultimately leading to asphalt recycling. An additional stakeholder is the incineration plants, which have a particular role within the reverse supply chain, namely the thermal cleaning of contaminated RAP material, especially tar-containing RAP material.

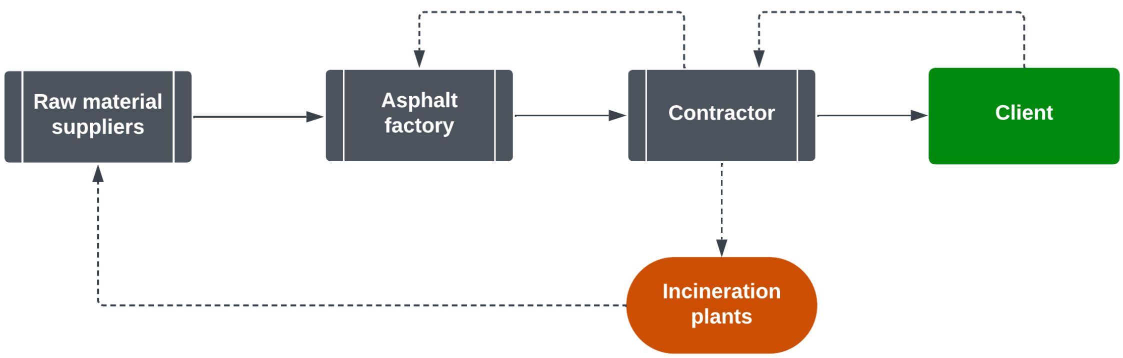

Figure 6.1: Schematic Overview of the Closed-Loop Supply Chain of the Road Construction Sector.

The following sections briefly describe the roles and processes of the four key stakeholders. For a more detailed analysis of the asphalt supply chain, including raw material suppliers, road management, road maintenance, and more, refer to Appendix IV – Asphalt Supply Chain Analysis.

6.1.1 Raw Material Suppliers

Raw material suppliers are the starting point of the asphalt supply chain. They provide essential materials to asphalt plants, including coarse and fine aggregates, filler (aggregates), bitumen, ECO-granulate (thermally cleaned RAP material by incineration plants), and additives [23].

The goal of a circular asphalt market is to minimise the use of new aggregates, bitumen, and additives and to maximise recycling efforts, as outlined in initiatives like Rijkswaterstaat's roadmap for transitioning the road construction sector [1].

6.1.2 Asphalt Plants

Asphalt plants represent the second phase of the supply chain. These facilities receive raw materials from suppliers and process them into asphalt. The production process includes weighing and mixing asphalt components, and depending on the production method, asphalt plants are categorised into three types: discontinuous (i.e., batch), semi-continuous, and continuous [24].

The production process generally involves several steps: (1) storing raw materials, (2) pre-dosing, (3) drying, (4) heating, (5) dosing, and (6) mixing. Asphalt plants also play a crucial role in reusing RAP material, which becomes available during road maintenance and reconstruction, providing it is not contaminated. If testing shows that the RAP material is contaminated (tar-contamination), the material is first thermally cleaned at an incineration plant, which results in the raw material ECO-granulate [24].

Recycling clean RAP material can be done using two main methods: cold reuse (on-site) and warm reuse (at the asphalt plant). Warm reuse typically results in higher-quality recycled asphalt and is often preferred [25]. Appendix IV - Asphalt Supply Chain Analysis provides detailed information about the asphalt recycling process and available methods.

6.1.3 Contractors

Contractors are the third phase of the supply chain. They are responsible for transporting asphalt from the asphalt plants to construction sites and executing the construction process [26]. In the reverse supply chain, contractors handle road maintenance, milling and repaving operations.

Maintenance works aim to address damages effectively and are categorised into minor and major maintenance work. The work can range from minor repairs with bitumen emulsion to major reconstructions with new asphalt surfaces. Major maintenance often involves asphalt milling, producing RAP material that can be reused on-site or transported back to asphalt plants for recycling [27].

6.1.4 Clients

Clients represent the final stage of the forward supply chain and the beginning of the reverse supply chain. Clients commission roads, which are then used to enable the mobility of people and goods until maintenance or reconstruction is needed.

Effective road management requires a systematic approach based on reliable data from road design, visual inspections, and measurements. This data helps predict, plan, and report future maintenance needs. When a road requires maintenance, it is temporarily transferred to a contractor through an existing maintenance contract or a tender process [27].

6.2 Asphalt Market Stakeholder Interviews

The supply chain analysis offers a theoretical understanding of the operation of the asphalt market but lacks practical insights about the reverse supply chain. While the literature review clarifies the supply chain stakeholders and material flows, this section complements the analysis with practical knowledge gained from interviews. These interviews involve four stakeholder groups, each providing a distinct perspective on recycling, sustainability, asphalt banks, and general innovation within the Dutch road construction sector, mainly the reverse supply chain. Specifically, the interviews focus on stakeholders in the Amsterdam Transport Region, including road authorities and managers, contractors and sub-contractors, asphalt producers, and third parties.

This paragraph summarises the key points from the interviews for each stakeholder group, highlighting the agreements and disagreements among the interviewees within each group regarding practices and developments in the reverse supply chain. The methodology for these interviews is designed to gather insights from key stakeholders within the Amsterdam Transport Region's reverse supply chain. A semi-structured interview format is selected to balance structured guidance and flexibility, allowing in-depth exploration of relevant topics while adapting to the interviewees' responses. The interviewees were chosen based on their active involvement in the reverse supply chain, focusing on three main categories: clients and asset managers, contractors and sub-contractors, and asphalt producers. Additionally, a third-party asphalt recycling organisation was involved to provide a diverse and balanced perspective.

The interview questions were tailored to each stakeholder group to address specific topics such as maintenance strategies, logistical processes, challenges in asphalt production, and future visions for reusing Reclaimed Asphalt Pavement (RAP) material and developing an asphalt bank. Data was collected through face-to-face and Microsoft Teams interviews, with audio recordings ensuring accurate transcription and analysis.

The methodological approach ensured a comprehensive understanding of stakeholder perspectives, challenges, and visions, contributing valuable insights into the dynamics of the reverse asphalt supply chain within the Amsterdam Transport Region. Further detailed information about the interview methodology, questions, and results is provided in Appendix V – Interview Methodology, Appendix VI – Interview Questions, and Appendix VII – Interview Results, respectively.

6.2.1 Road Authorities and Managers

This research contains interviews with three key road authorities within the Amsterdam Transport Region: ***Road Authority 1***, ***Road Authority 2***, and ***Road Authority 3***. These interviews provide practical insight into the reverse supply chain and the dependency on maintenance strategies regarding the available volumes of Reclaimed Asphalt Pavement (RAP) material. This section highlights the essential information from each interview, focusing on similarities and differences.

6.2.1.1 Interview Highlights Road Authorities

Highlights Interview with Specialist Road Construction Materials of Road Authority 1 [28]

- **Road Structures**: Since 2008, Road Authority 1 has accepted more advanced asphalt mixtures, resulting in thinner road constructions when compared to the traditionally 24-centimetre thick road structures. This change has introduced significant variations in road structures. There is, thus, no standard road topology for the roads under management by Road Authority 1.

- **Maintenance Strategies**: Road Authority 1's maintenance strategy depends on annual inspections, informing a flexible five-year maintenance plan. The maintenance strategies include major maintenance (renewing entire road sections) and variable maintenance (repairing specific damages).
- **Reuse of RAP Material**: Road Authority 1 allows relatively high reuse percentages (60-70%) in base and binder layers. After a strict validation process, Road Authority 1 permits 30-60% reuse in surface layers; however, 30% reuse is more commonly applied. Challenges include logistics and quality control.
- **Future Vision**: Road Authority 1 aims for climate-neutral asphalt by 2050, with intermediate goals before 2050 to increase recycled material content, integrate bio-based materials, enhance quality control, and standardise reuse practices.

Highlights Interview with Paving Management Advisor of Road Authority 2 [29]

- **Road Structures and Maintenance**: In 2010, Road Authority 2 transitioned to a regional contract approach. The current maintenance strategy, therefore, focuses on surface layer replacement and local reinforcements, with mid-lifespan reinforcement or replacement of the binder layer after around 30 years.
- **Reuse of RAP Material**: Road Authority 2 allows reuse rates up to 50% in surface layers, with pilot projects exploring higher percentages. The base and binder layers are not restricted. Challenges include balancing old bitumen with new bitumen and maintaining quality control.
- **Future Vision**: Road Authority 2 emphasises innovation and sustainability, contractual shared risks, and reliance on Asfaltkwaliteitloket (AKL) for technology validation. Road Authority 2 focuses on long-term sustainability over short-term gains.

Highlights Interview with Asset Management Consultant of Road Authority 3 [30]

- **Road Pavement Construction**: Road Authority 3 has shifted from standardised to more variable road constructions based on traffic loads. Due to height restrictions and careful planning, additional variation due to maintenance is limited.
- **Maintenance and Reconstruction**: The current reuse rates are 60-70% for base and binder layers and up to 50% for surface layers. Challenges include the availability of RAP material and quality control. There are ongoing efforts to improve quality control and availability.
- **Future Vision**: Road Authority 3 emphasises sustainable asphalt production, transitioning to warm-mix and, eventually, cold-mix asphalt, and explores regional asphalt banks to enhance material availability and quality control.

6.2.1.2 Agreements and Disagreements among Road Authorities

Agreements

- **Reuse of Materials**: All road authorities agree on the importance of reusing RAP material. Road Authority 1, Road Authority 2, and Road Authority 3 highlight the current practices and challenges (logistics, quality control, and RAP material availability) associated with high-reuse percentages in different asphalt layers.
- **Sustainability Goals**: There is a consensus on sustainable road maintenance practices. All the interview authorities discuss their future vision for improving sustainability through innovative maintenance techniques and optimised material reuse.
- **Maintenance Strategies**: Each of the interviewed authorities emphasises the significance of tailored maintenance strategies based on road conditions that focus on extending road lifespans and minimising environmental impacts.

Disagreements/differences

- **Maintenance Approaches:**
    - Road Authority 1 discusses a comprehensive approach on a national level with regional adaptations.
    - Road Authority 2 focuses on a regional approach, with its road network divided into seven zones, each contracted by a contractor responsible for the maintenance.
    - Road Authority 3 emphasises careful planning and selective reconstruction specific to the constraints and needs of Amsterdam.
- **Recycling Methods and Innovation:**
    - Road Authority 1 discusses integrating bio-based materials and controlled rejuvenation of mastic.
    - Road Authority 2 proposes the appointment of Asfaltkwaliteitloket to validate new technologies. In addition, Road Authority 2 explores the use of recycling trains.
    - Road Authority 3 discusses transitioning to warm-mix and, eventually, cold-mix asphalt and leveraging regional asphalt banks.
- **Vision on Regional Asphalt Banks:**
    - Road Authority 1 and Road Authority 2 support the concept of regional asphalt banks for optimising quality control and sustainability.
    - Road Authority 3 acknowledges the potential benefits of improving material availability but highlights practical challenges and stresses the need for clear guidelines and procedures.

6.2.1.3 Conclusion

While the road authorities agree on most of the interview content, namely the importance of sustainability and material reuse among the road authorities and managers, specific approaches and strategies for maintenance, innovation, and recycling vary. These differences reflect the diverse needs and conditions faced by the three road authorities who operate on different spatial scales. In general, the opinions of the three parties are remarkably similar.

6.2.2 Contractors and Subcontractors

Interviews with contractors and subcontractors involved in the asphalt supply chain included ***Contractor 1***, ***Contractor 2*** and ***Contractor 3***, contractors in the Dutch road construction sector. These interviews offer valuable insight into the challenges and opportunities associated with asphalt milling, processing, and reusing Reclaimed Asphalt Pavement (RAP) material. This section presents the essential information from each interview, focusing on commonalities and differences.

6.2.2.1 Interview Highlights Contractors and Subcontractors

Highlights Interview with Head of Material Science of Contractor 1 [31]

- **Outdated Specifications:** Contractor 1 finds the use of RAW specifications (a standard specification system in the Dutch civil engineering sector) by municipalities to be one of the factors limiting innovation. The RAW specifications rely on well-established data but are not up-to-date.

- **Trust Issues**: The construction fraud scandal* has led to a lack of trust between clients and contractors, further limiting innovation.
- **Financial Risks**: New technology poses financial risks for clients, also hampering innovation.
- **Pioneering Fund Proposal**: Contractor 1 states that establishing a central fund that mitigates financial risks for organisations (contractors and governmental organisations) in innovation projects could encourage further pioneering.
- **Quality Assessment**: High-quality reuse of RAP material will require improved initial quality assessment of the asphalt pavement.
- **Asphalt Bank Vision**: A regional asphalt bank can optimise logistics and sustainability but will require separate milling and processing of asphalt layers.
- **Research Outcomes**: The research should demonstrate the impact of a regional asphalt bank on the logistics and sustainability of RAP material.

Highlights Interview with Technical Manager of Contractor 2 [32]

- **Milling Process**: The milling process of asphalt pavement first requires a control check for tar. After that, the milling starts. The asphalt layers are milled preferably separately to yield higher-quality RAP material. However, in practice, this only happens sparingly.
- **Recycling Challenges**: A significant recycling challenge is rejuvenating old bitumen and the limited storage capacity of asphalt plants.
- **Processing Issues**: The high recycled content in asphalt mixtures leads to more variability and broader quality control margins. In combination with lower asphalt temperatures, this results in significant processing challenges on location, especially with application by hand.
- **Asphalt Banks**: A regional asphalt bank could reduce transport costs and improve efficient RAP material reuse.
- **Industry Challenges**: The significant challenges road contractors face are personnel shortages, working hours, innovative constraints, and reuse limitations. Additionally, bitumen quality has been declining over the years. That also impacts initial asphalt quality.

Highlights Interview with Director of Contractor 3 [33]

- **Milling Instructions**: The guidance and instructions from the main contractors on the milling approach affect quality and efficiency. For example, if the main contractor demands separate milling, quality improves, but efficiency decreases. As a subcontractor, you have no choice but to do what the customer asks.
- **Milling Process**: The milling process itself is straightforward. Only some adjustments are made based on machine performance and milling resistance by the asphalt, which is crucial for efficiency.
- **Transport Logistics**: Transport planning is complex; in most situations, issues affect logistics. Issues like truck shortages are common and impact milling operations, causing stops in the milling process.
- **Asphalt Bank Vision**: Contractor 3 supports the concept of an asphalt bank but stresses the need for broad cooperation and financial incentives for contractors.

* The Dutch construction fraud scandal , uncovered in 2001, involved major construction companies in the Netherlands conspiring to fix prices and rig bids for public projects, leading to inflated costs and widespread corruption within the industry. The scandal exposed deep-rooted issues in the country's construction sector, resulting in legal action, fines, and reforms to improve transparency and competition [36].

- **Future Challenges**: Towards the future, separate milling operations will become more prevalent; however, innovative opportunities for subcontractors like Contractor 3 will be limited. Main contractors should initiate innovation projects.

6.2.2.2 Agreements and Disagreements between Contractors and Subcontractors

Agreements

- **Need for Improved Quality and Recycling Practices**: All the contractors and subcontractors highlight the importance of better quality assessment and recycling practices for RAP material. Contractor 1 emphasises initial quality assessment improvements, Contractor 2 discusses the necessity of rejuvenation agents, and Contractor 3 underscores the impact of the milling process on the RAP material quality.
- **Support for Regional Asphalt Bank**: All the contractors and subcontractors see potential benefits in establishing regional asphalt banks. Contractor 1 states that these banks could enhance logistics and sustainability, while Contractor 3 highlights the need for adequate storage capacity and sector cooperation.
- **Challenges with Innovation**: There is a consensus on the challenges faced by adopting new technologies. Contractor 1 mentions financial risks, Contractor 2 notes regulatory and validation struggles, and Contractor 3 acknowledges limited innovation opportunities for subcontractors.

Disagreements

- **Impact of Separate Milling**: While Contractors 1 and 2 support separate milling for better quality, Contractor 3 mentions that separate milling, although beneficial, also requires extra effort and preparation, indicating practical challenges.
- **Storage and Logistics**: Contractors 1 and 2 point out the logistical challenges and limited storage capacity, whereas Contractor 3 focuses on the complexity of transport logistics and the need for better planning and backhauling practices.
- **Role of Contractors and Subcontractors in Innovation**: Contractor 1 suggests that contractors and clients should improve transparency and communication to foster innovation. In contrast, Contractor 3 emphasises that subcontractors like Contractor 3 have limited roles in driving innovation, focusing instead on maximising machine performance.

6.2.2.3 Conclusion

The interviews reveal a comprehensive perspective on the current state and future challenges of the asphalt supply chain, particularly concerning innovation, recycling practices, and the potential benefits of regional asphalt banks. There is a general agreement on the need for improved quality and logistics. The interviews only highlight very few specific areas of disagreement and some unique challenges faced by the different stakeholders within the industry, but in general, the three parties universally agree on the challenges faced in the future.

6.2.3 Asphalt Producers

In examining the role of asphalt producers within the Amsterdam Transport Region, insights by industry parties focus on the production, storage, and recycling practices of asphalt. The interview with a representative of ***Asphalt Producer 1***, three asphalt plants in the Netherlands, sheds light on the operational dynamics of asphalt plants in Amsterdam, Rotterdam, and Tiel. This information details the asphalt production process and reuse of Reclaimed Asphalt Pavement (RAP) material. This section highlights critical points from the interview with the asphalt producers.

6.2.3.1 Interview Highlights Asphalt Producers

Highlights Interview with Manager Innovation & Quality of Asphalt Producers 1 [34]

- **Production Data**: The asphalt plants produce an average of 400,000 to 550,000 tons of asphalt annually per plant. Approximately 50% of the raw materials consists of RAP material.
- **Storage Capacity**: To store the RAP material required, the asphalt plant in City A has a storage capacity of 5,000 to 15,000 tons, and the plant in City B has a capacity of 20,000 to 25,000 tons.
- **Milling and Acceptance**: The intake process of RAP material distinguishes between base-layer and surface-layer milling material. The intake procedure conforms to the CROW guidelines and requires checks for tar contamination and verification of available storage capacity.
- **Storage Process**: The storage process of RAP material is straightforward: RAP material is stored by fraction size to ensure homogeneity and rapid turnover for high-flow fractions.
- **Recycling Rates**: The recycling rates for base and binder layers are up to about 70%, with theoretical recycling rates of up to 100% using ECO-granulate. ECO-granulate is RAP material thermally cleaned to remove tar contamination. Recycling rates for surface layers can vary significantly.
- **Asphalt Bank Vision**: A regional asphalt bank could streamline the storage of multiple fractions of high-quality RAP material. However, producers think an asphalt bank should arise from natural market competition, not government intervention.
- **Challenges and Solutions**: Future challenges for the asphalt plants included ensuring the homogeneity of RAP material and managing their limited storage capacities. The limited storage capacity of asphalt plants might even naturally evolve into coordinated storage of RAP material among multiple asphalt plants to maintain efficiency and potentially become something like an asphalt bank.

6.2.4 Third Parties

Additionally, the perspective of a third-party stakeholder, ***Third Party 1***, is provided. The interview with ***Third Party 1's*** representative gives an in-depth look at the company's processing techniques, logistical structure, and competitive landscape. The company's expertise is in processing PA16 asphalt pavements, and its unique market position highlights interesting aspects of the reverse asphalt supply chain in the Amsterdam Transport Region. The insights gathered from this interview contribute to a broader understanding of the asphalt market dynamics and potential challenges faced by asphalt banks in the asphalt supply chain. This section summarises the key points from the interview.

6.2.4.1 Interview Highlights Third Parties

Highlights Interview with Manager of Third Party 1 [35]

- **Production and Processing**: Third Party 1 specialises in processing PA16 asphalt by crushing, sieving, and filtering PA16 milled material. This process results in three fractions: 0/5, 5/8, and 8/16. These fractions are reused in various asphalt applications, with 8/16 primarily in new PA mixes.
- **Storage and Logistics**: One of the strengths of Third Party 1 is managing logistics efficiently and using ships for transport to minimise costs. Third Party 1 emphasises just-in-time delivery to meet project timelines and contractor budgets.
- **Competitive Landscape**: Third Party 1 competitors are non-partnering road construction contractors like KWS, BAM and Heijmans, who also use PA16 RAP material. However, the company's fixed location ensures control over quality compared to the mobile installations of its competitors like AsfaltNu. In short, the form of Third Party 1, like an asphalt bank, is unique to the Netherlands.

- **Customer Segments**: Third Party 1 serves partnering road construction contractors and asphalt plants, focusing on reuse in PA mixes.
- **Regulations and Sustainability**: Third Party 1 advocates for the certification of processing companies to make processed RAP material a certified second-hand raw material, resulting in better material management under European regulations.
- **Challenges and Solutions**: Third Party 1 foresees challenges in recycling asphalt containing Polymer Modified Bitumen (PMBs), quality control of circular materials, and production control with high amounts of asphalt recycling. It, therefore, argues for the necessity of pre-processing RAP material, balancing the regional RAP supply and separate asphalt layer milling.
- **Future Industry Challenges**: Future challenges include consistent bitumen quality, low-temperature asphalt production, and government support for sustainable practices.

6.3 Thematic Analysis of the Interviews

The thematic analysis identifies and summarises essential themes and insights from each stakeholder group. The interviews among four stakeholder groups, road authorities and managers, contractors and subcontractors, asphalt producers, and third parties, provide a diverse insight into the current asphalt supply chain regarding the production, use, and management of RAP material and the development of regional asphalt banks, among other topics. This paragraph provides cross-stakeholder group similarities and contradictions and summarises the general insight of the interviews. Appendix V – Interview Methodology provides further detailed information about the thematic analysis methodology.

6.3.1 Cross-Stakeholder Similarities and Contradictions

Similarities

1. **Support for Regional Asphalt Banks**: All stakeholders see the value in developing regional asphalt banks to streamline the reuse of Reclaimed Asphalt Pavement (RAP) materials. They agree on the potential benefits for logistics, material quality, and potential cost savings.
2. **Focus on Sustainability**: There is a shared commitment to increase the use of recycled materials and promote circular and climate-neutral practices. All stakeholder groups recognise the environmental benefits and regulatory pressures driving this trend.
3. **Challenges in Material Reuse**: Common challenges include logistical issues, quality control, and the better integration of recycled materials into the asphalt supply chain. Stakeholders agree that overcoming these challenges requires collaboration and innovation.

Contradictions

1. **Personal Interests vs. Regional Cooperation**: While road authorities and clients emphasise the need for regional cooperation, contractors and producers sometimes face conflicts between individual interests and regional or national goals. These can create tension in implementing broader strategies for material reuse, which require sector-wide cooperation.
2. **Validation Processes**: Clients and road authorities often have stringent validation processes to ensure the quality of recycled materials, which slows down the adoption of innovation. In contrast, contractors and producers view these processes as overly restrictive and advocate for more flexible approaches to encourage innovation.
3. **Investment in Technology**: Asphalt producers and third parties focus more on technological advancements to improve recycling processes. However, clients and road authorities prioritise regulatory compliance and long-term maintenance strategies over immediate technological investments.

6.3.2 Summary of Key Insights

Reuse and Recycling of Reclaimed Asphalt Pavement (RAP)

1. There is a strong emphasis among the stakeholders on increasing the percentage of reclaimed asphalt in new road constructions, with varying opinions on the success and acceptance among the stakeholders.
2. The challenges for increasing recycling rates, identified by the stakeholders, include logistical issues, material availability, and stringent validation processes. However, certain stakeholder groups might (partly) disagree.

Regional Asphalt Banks

1. The stakeholders are generally satisfied with the possible existence of a regional asphalt bank and view it as a critical component for the efficient recycling and reuse of asphalt.
2. Various stakeholders highlighted that a regional asphalt bank requires better quality management, regional collaboration, and overcoming personal interests.

Sustainability Practices and Future Visions

1. Generally, the move towards circular and climate-neutral pavements is a common goal among the stakeholders. However, the approach and view of the individual stakeholders on achieving these objectives differ.
2. Road authorities and managers consider life-extending maintenance strategies but need better integration into existing maintenance frameworks.

Innovation and Development

1. Stakeholders focus on innovations in asphalt production and maintenance processes, considering changes to road management, maintenance techniques, and asphalt production processes.
2. Contractors and asphalt producers state the need for more flexible procurement and validation processes to encourage using recycled materials and innovation.

6.4 Conclusion

This chapter presents a theoretical overview of the asphalt supply chain in the Netherlands, supplemented by practical insights specific to the reverse supply chain in the Amsterdam Transport Region derived from stakeholder interviews. Initially, the chapter outlines the literature-based understanding of the Dutch asphalt supply chain. Subsequently, it incorporates practice-oriented details gathered from interviews with various stakeholders in the Amsterdam Transport Region.

The thematic analysis offers an understanding of current practices, challenges, and future directions in utilising recycled asphalt and developing asphalt banks in the Netherlands and regions like the Amsterdam Transport Region. Each stakeholder group provides unique insights, reflecting their distinct roles and experiences in the asphalt sector.

The analysis highlights a collective interest among stakeholders in enhancing the sustainability and efficiency of asphalt production and maintenance through the increased use of recycled materials and the establishment of regional asphalt banks. However, realising these objectives necessitates overcoming challenges in logistics, quality control, and regulatory processes. The commonalities among stakeholders reveal shared goals and potential collaboration opportunities, while the differences underscore the need for balanced approaches that account for the perspectives and constraints of all parties involved.

7 Modelling the Asphalt Bank and the Asphalt Supply Chain

This chapter delves into the comprehensive design and analysis of the model used to assess the asphalt supply chain in the Amsterdam Transport Region. It outlines the key considerations in developing the model, the mathematical framework underlying it, and the case studies and sensitivity analyses employed to evaluate different supply chain scenarios. The chapter is structured as follows:

- **Paragraph 7.1 Model Design Considerations** – This section discusses the model development process, highlighting the selection of a Mixed Integer Linear Programming (MILP) model, the choice of Python-MIP for implementation, and the model's core components.
- **Paragraph 7.2 Mathematical Optimisation Model** – Based on the design considerations, this section presents the mathematical formulation of the MILP model, detailing the objective function and the constraints to ensure realistic solutions. This section also introduces the parameters and decision variables critical to the model's function.
- **Paragraph 7.3 Case Studies and Sensitivity Analysis** – The chapter then shifts to the illustration of the model application through three case studies, each examining different supply chain scenarios. This section also introduces the sensitivity analysis to explore the robustness of the model under varying conditions.
- **Paragraph 7.4 Conclusion** – Finally, the conclusion summarises the model's structure, the theoretical foundations, and the strategic approach to case studies and sensitivity analysis. That sets the stage for the detailed results, analysis and insights offered in the next chapter.

7.1 Model Design Considerations

The model design underwent numerous iterations throughout the research project, leading to the final design presented in this research report. Preliminary research determined that a MILP model would be the most suitable for the project's objectives and requirements, as discussed in Chapter 3, Theoretical Framework. A MILP model requires a modelling program for performing calculations and simulations. As detailed in Chapter 4, Methodology, Python with the Python-MIP package was chosen for this purpose. The model development and simulations are performed using Python-MIP and the pre-installed CBC (COIN-OR) solver.

The model was constructed within the Python environment using various scripts called from a main script, ensuring clarity and efficiency. The model comprises four essential components: parameters, decision variables, constraints, and the objective function. Each component's design was informed by literature, practical knowledge from the stakeholder interviews, and general logic, aiming to create a logical and realistic representation of the asphalt supply chain within the Amsterdam Transport Region.

Appendix VIII – Model Design Considerations provides an extensive explanation of all design choices, including the general design of the Python project, the parameters used, their sources, the decision variables, and model limits. Thus, this appendix offers a comprehensive overview of the model and the design decisions. The following paragraph describes the mathematical formulation of the MILP model, which can be directly derived from the choices detailed in Appendix VIII – Model Design Considerations.

7.2 Mathematical Optimisation Model

The previous paragraph and Appendix VIII – Model Design Considerations, provide detailed information on the design choices and supporting information sources. This paragraph introduces the mathematical formulation of the model based on those choices.

The mathematical optimisation model was developed to analyse two scenarios: (1) an asphalt supply chain scenario without an asphalt bank and (2) an alternative scenario incorporating an asphalt bank. The objective is to compare the optimised supply chains under both scenarios to identify the most cost-efficient solution. The optimisation model determines the optimal location for the asphalt bank and the optimal quantities of asphalt production, including the use of Reclaimed Asphalt Pavement (RAP) and raw materials for each asphalt plant in the region. The base scenario, in contrast, only optimises the quantities of asphalt produced and the materials used by each plant.

7.2.1 Indices, Parameters, and Decision Variables

This section outlines the base components of the MILP model, which include indices, parameters, and decision variables, the elements that make up the model and facilitate the optimisation process.

7.2.1.1 Model Indices

Table 7.1 presents the indices representing various sets, such as months, road sections, and suppliers, which help categorise and reference different elements within the model.

Table 7.1: Model Indices

Indices	
$\boldsymbol{t} \in \boldsymbol{T}$	Set of months.
$\boldsymbol{s} \in \boldsymbol{S}$	Set of road sections.
$\boldsymbol{l} \in \boldsymbol{L}$	Set of maintenance sites.
$\boldsymbol{w} \in \boldsymbol{W}$	Set of raw material suppliers.
$\boldsymbol{b} \in \boldsymbol{B}$	Set of candidate asphalt banks.
$\boldsymbol{p} \in \boldsymbol{P}$	Set of asphalt plants.
$\boldsymbol{z} \in \boldsymbol{Z}$	Set of maintenance zones.

Note: the base scenario does not contain the indices related to the candidate asphalt bank ($b \in B$), as the base scenario contains no asphalt bank.

7.2.1.2 Parameters

Table 7.2 to Table 7.10 represent the model parameters like economic, technical, and physical parameters, providing essential data like costs, capacities, locations, and distances that influence the model's decision-making.

Table 7.2: Asphalt Mixture Parameters

Asphalt Mixture Parameters	
$\boldsymbol{Pr_{cr}}$	Portion/percentage of coarse aggregates in a cubic metre of raw material.
$\boldsymbol{Pr_{fi}}$	Portion/percentage of fine aggregates in a cubic metre of raw material.
$\boldsymbol{Pr_{sa}}$	Portion/percentage of natural sand in a cubic metre of raw material.
$\boldsymbol{Pr_{fl}}$	Portion/percentage of filler aggregates in a cubic metre of raw material.
$\boldsymbol{Pr_{bi}}$	Portion/percentage of bitumen in a cubic metre of raw material.

The portion size of each of these materials depends on the asphalt mixture. The portion sizes are represented as a percentage of one cubic metre of raw material and add up to 100% or the mass of one cubic metre.

Table 7.3: Economic Parameters.

Economic Parameters	
P_{trans}	Dutch price for transporting a cubic metre of material for one kilometre.
P_{hand}	Dutch price for loading and unloading (handling) a cubic metre of material.
P_{cr}	Dutch price for a cubic metre of coarse aggregates.
P_{fi}	Dutch price for a cubic metre of fine aggregates.
P_{sa}	Dutch price for a cubic metre of natural sand.
P_{fl}	Dutch price for a cubic metre of filler aggregates.
P_{bi}	Dutch price for a cubic metre of bitumen.
P_{rap}	Dutch price for pre-processing RAP material.
r_{annual}	Annual inflation rate.
$r_{monthly}$	Monthly inflation rate.

Table 7.4: Road Section Parameters.

Road Section Parameters	
A_s	The surface area of road section s.
T_s^{top}	Asphalt thickness of the asphalt surface layer for road section s.
L_s^{top}	The lifespan of the asphalt surface layer for road section s.
T_s^{bin}	Asphalt thickness of the asphalt binder layer for road section s.
T_s^{base}	Asphalt thickness of the asphalt base layer for road section s.
C_s	The construction date of road section s.

Table 7.5: Maintenance Parameters.

Maintenance Parameters	
$R_{top,t,l}$	Available RAP volume from the asphalt surface layer at maintenance site l in month t.
$R_{bin,t,l}$	Available RAP volume from the asphalt binder layer at maintenance site l in month t.
$R_{base,t,l}$	Available RAP volume from the asphalt base layer at maintenance site l in month t.

Table 7.6: Raw Material Supplier Parameters.

Raw Material Supplier Parameters	
L_W	Location of raw material supplier w.

Table 7.7: Candidate Bank Parameters.

Candidate Bank Parameters	
L_b	Location of candidate bank b.
P_{bank}	Dutch price for one square metre of land for candidate asphalt bank b.
set_{cap}	Maximum storage capacity for selected asphalt bank b.

Note: the base scenario does not contain the candidate bank parameters, as the base scenario contains no asphalt banks.

Table 7.8: Asphalt Plant Parameters.

Asphalt Plant Parameters	
$\boldsymbol{L_p}$	Location of asphalt plant p.
$\boldsymbol{C_p^{prod}}$	Monthly production capacity of asphalt plant p.
$\boldsymbol{C_p^{rap}}$	RAP material storage capacity of asphalt plant p.
$\boldsymbol{C_p^{raw}}$	Raw material storage capacity of asphalt plant p.

Table 7.9: Maintenance Zone Parameters.

Maintenance Zone Parameters	
$\boldsymbol{R_{top,t,z}}$	Required asphalt volume for the asphalt surface layer at maintenance zone z in month t.
$\boldsymbol{R_{bin,t,z}}$	Required asphalt volume for the asphalt binder layer at maintenance zone z in month t.
$\boldsymbol{R_{base,t,z}}$	Required asphalt volume for the asphalt base layer at maintenance zone z in month t.

Table 7.10: Calculated distances.

Calculated Distances	
$\boldsymbol{d_{l,b}}$	Calculated distance from maintenance site l to asphalt bank b.
$\boldsymbol{d_{b,p}}$	Calculated distance from asphalt bank b to asphalt plant p.
$\boldsymbol{d_{w,p}}$	Calculated distance from raw material supplier w to asphalt plant p.
$\boldsymbol{d_{p,z}}$	Calculated distance from asphalt plant p to maintenance zone z.

Note: the base scenario does not include the calculated distance from the asphalt bank to the asphalt plants ($d_{b,p}$), as the base scenario contains no asphalt bank. Additionally, instead of calculating the distance between the maintenance site and an asphalt bank ($d_{l,b}$), the distance is calculated between the maintenance site and an asphalt plant ($d_{l,p}$), meaning RAP material is transported directly to the asphalt plants.

7.2.1.3 Decision Variables

Finally, the decision variables capture the choices the model can make, such as quantities of materials to transport or produce, which are optimised to achieve the model's objective under different scenarios. The next part of this section discusses the decision variables applicable to this MILP model.

Maintenance Work Decision Variables

- $r_{l,b,t}^{top}$: Continuous decision variable representing the supply of RAP materials from the asphalt top layer from maintenance site l to asphalt bank b in month t.
- $r_{l,b,t}^{bin}$: Continuous decision variable representing the supply of RAP materials from the asphalt bin layer from maintenance site l to asphalt bank b in month t.
- $r_{l,b,t}^{base}$: Continuous decision variable representing the supply of RAP materials from the asphalt base layer from maintenance site l to asphalt bank b in month t.

Note: in the base scenario, these decision variables are changed to represent the supply of RAP materials from a specific asphalt layer from maintenance site l to asphalt plant p in month t. The base scenario decision variables look like $r_{l,p,t}^{top}, r_{l,p,t}^{bin}, and\ r_{l,p,t}^{base}$.

Raw Material Supplier Decision Variables

- $t_{w,p,t}^{raw}$: Continuous decision variable representing the supply of raw materials from supplier w to asphalt plant p in month t.

Asphalt Plant Decision Variables

- $p_{p,t}^{top}$: Continuous decision variable representing the production of asphalt for the top layer at asphalt plant p in month t.
- $p_{p,t}^{bin}$: Continuous decision variable representing the production of asphalt for the bin layer at asphalt plant p in month t.
- $p_{p,t}^{base}$: Continuous decision variable representing the production of asphalt for the base layer at asphalt plant p in month t.
- $spc_{p,t}$: Continuous decision variable representing the slack production capacity at asphalt plant p in month t.
- $ssc_{p,t}$: Continuous decision variable representing the slack storage capacity at asphalt plant p in month t.
- $prp_{p,t}^{top}$: Continuous decision variable representing the RAP material processed for the top layer at asphalt plant p in month t.
- $prp_{p,t}^{bin}$: Continuous decision variable representing the RAP material processed for the bin layer at asphalt plant p in month t.
- $prp_{p,t}^{base}$: Continuous decision variable representing the RAP material processed for the base layer at asphalt plant p in month t.
- $prw_{p,t}^{top}$: Continuous decision variable representing the raw material processed for the top layer at asphalt plant p in month t.
- $prw_{p,t}^{bin}$: Continuous decision variable representing the raw material processed for the bin layer at asphalt plant p in month t.
- $prw_{p,t}^{base}$: Continuous decision variable representing the raw material processed for the base layer at asphalt plant p in month t.
- $s_{p,t}^{rap}$: Continuous decision variable representing the RAP material stored at asphalt plant p in month t.
- $s_{p,t}^{raw}$: Continuous decision variable representing the raw material stored at asphalt plant p in month t.

Note: the base scenario has an additional slack decision variable, the RAP storage slack ($ssc_{p,t}$). The base scenario has no asphalt bank and thus lacks RAP storage capacity. This decision variable can provide more RAP storage capacity beyond the "normal" RAP storage capacity if required.

Transport Decision Variables

- $t_{p,z,t}^{top}$: Continuous decision variable representing the transport of asphalt for the top layer from asphalt plant p to maintenance zone z in month t.
- $t_{p,z,t}^{bin}$: Continuous decision variable representing the transport of asphalt for the bin layer from asphalt plant p to maintenance zone z in month t.
- $t_{p,z,t}^{base}$: Continuous decision variable representing the transport of asphalt for the base layer from asphalt plant p to maintenance zone z in month t.

Binary Decision Variables

- $ps_{p,z,t}$: Binary decision variable indicating whether asphalt plant p is selected for supplying asphalt to maintenance zone z in month t.
- bs_b: Binary decision variable indicating whether asphalt bank b is utilised.

Note: the base scenario does not include the binary decision variable indicating whether an asphalt bank is utilised, as the base scenario does not contain an asphalt bank.

Asphalt Bank Decision Variables

- u_b: Continuous decision variable representing the capacity of asphalt bank b.
- $t^{rap}_{b,p,t}$: Continuous decision variable representing the transport of RAP materials from asphalt bank b to asphalt plant p in month t.
- $rb_{b,t}$: Continuous decision variable representing the RAP material stored at asphalt bank b in month t.

Note: the base scenario does not include the asphalt bank decision variables, as the base scenario has no asphalt bank.

7.2.2 Model Objective

The primary goal of the model is to minimise the total costs of the asphalt supply chain scenarios, as expressed in Eq. (1):

$$Min\ C = TC + HC + BC + RMC + RPC \qquad \text{(Eq. (1))}$$

Here, C represents the total costs in Euros, including:

- **Transportation Costs** (TC): Costs related to transporting raw materials, RAP, and asphalt between different locations within the Amsterdam Transport Region [€].
- **Handling Costs** (HC): Costs related to loading and unloading materials at the asphalt bank and asphalt plants handling the material [€].
- **Asphalt Bank Costs** (BC): One-time costs for purchasing the land required for the asphalt bank [€].
- **Raw Material Costs** (RMC): Costs of purchasing raw materials from suppliers needed to produce asphalt [€].
- **RAP Processing Costs** (RPC): Costs of processing RAP material, namely breaking and sieving the milled asphalt [€].

Note: the model's objective function for the current asphalt supply chain scenario (the base scenario) disregards the asphalt bank costs.

Eq. (2) defines the transportation costs (TC):

$$TC = \left(\sum_{l \in L} \sum_{b \in B} \sum_{t \in T} d_{l,b} * \left(r^{top}_{l,b,t} + r^{bin}_{l,b,t} + r^{base}_{l,b,t}\right) + \sum_{b \in B} \sum_{p \in P} \sum_{t \in T} d_{b,p} * t^{rap}_{b,p,t} + \sum_{w \in W} \sum_{p \in P} \sum_{t \in T} d_{w,p} * t^{raw}_{w,p,t} + \sum_{p \in P} \sum_{z \in Z} \sum_{t \in T} d_{p,z} * \left(t^{top}_{p,z,t} + t^{bin}_{p,z,t} + t^{base}_{p,z,t}\right) \right) * \sum_{t \in T} P_{trans} / \left(\left(1 + r_{montly}\right)^{t}\right) \qquad \text{(Eq. (2))}$$

Where:

- $d_{l,b}, d_{b,p}, d_{w,p}, and\ d_{p,z}$ represent the distances between maintenance site l, asphalt bank b, raw material supplier w, asphalt plant p, and maintenance zone z [km].
- $r_{l,b,t}^{top}, r_{l,b,t}^{bin}, and\ r_{l,b,t}^{base}$ represent the quantities of top, bin, and base layer RAP material transported from maintenance site l to asphalt bank b in month t [m3].
- $t_{b,p,t}^{rap}$ represents the quantity of RAP material transported from asphalt bank b to asphalt plant p in month t [m3].
- $t_{w,p,t}^{raw}$ represents the quantity of raw material transported from supplier w to asphalt plant p in month t [m3].
- $t_{p,z,t}^{top}, t_{p,z,t}^{bin}, and\ t_{p,z,t}^{base}$ represent the quantities of top, bin, and base layer asphalt types transported from asphalt plant p to maintenance zone z in month t [m3].
- P_{trans} is the transport price per cubic metre of material per kilometre [€/m3/km].
- $r_{monthly}$ is the monthly inflation rate [%].

In the base scenario, the transport of RAP material from the asphalt bank to the asphalt plants is not considered. Instead, RAP material moves directly from the maintenance site to the asphalt plants. Therefore, the calculation of transportation costs in the base scenario differs from the asphalt bank scenario by eliminating the transport step from the asphalt bank to the asphalt plants and routing the RAP transport per asphalt layer (top, bin, and base) directly from the maintenance site to the asphalt plants.

Eq. (3) defines the handling costs (HC):

$$HC = \left(\sum_{l\in L} \sum_{b\in B} \sum_{t\in T} \left(r_{l,b,t}^{top} + r_{l,b,t}^{bin} + r_{l,b,t}^{base}\right) + \sum_{b\in B} \sum_{p\in P} \sum_{t\in T} t_{b,p,t}^{rap} + \sum_{w\in W} \sum_{p\in P} \sum_{t\in T} t_{w,p,t}^{raw} + \sum_{p\in P} \sum_{z\in Z} \sum_{t\in T} \left(t_{p,z,t}^{top} + t_{p,z,t}^{bin} + t_{p,z,t}^{base}\right) + \sum_{p\in P} \sum_{t\in T} ssc_{p,t}^{out} \right) * \sum_{t\in T} P_{hand} / \left((1 + r_{montly})^{t} \right) \quad \text{(Eq. (3))}$$

Where:

- $r_{l,b,t}^{top}, r_{l,b,t}^{bin}, and\ r_{l,b,t}^{base}$ represent the quantities of top, bin, and base layer RAP material transported from maintenance site l to asphalt bank b in month t [m3].
- $t_{b,p,t}^{rap}$ represents the quantity of RAP material transported from asphalt bank b to asphalt plant p in month t [m3].
- $t_{w,p,t}^{raw}$ represents the quantity of raw material transported from supplier w to asphalt plant p in month t [m3].
- $t_{p,z,t}^{top}, t_{p,z,t}^{bin}, and\ t_{p,z,t}^{base}$ represent the quantities of top, bin, and base layer asphalt types transported from asphalt plant p to maintenance zone z in month t [m3].
- P_{hand} is the price for handling, loading or unloading a cubic metre of material [€/m3].
- $r_{monthly}$ is the monthly inflation rate [%].

Similar to the transportation costs in the base scenario, the handling costs of RAP for transport from the asphalt bank to the asphalt plants are also not considered in the base scenario, as the RAP material flow is moved directly from the maintenance site to the asphalt plants. The base scenario also incurs extra handling costs for RAP material flowing out of temporary storage on construction sites, as it requires additional material handling. The green factor in Eq. (3) presents the extra handling costs.

Eq. (4) defines the one-time cost of acquiring an asphalt bank (BC):

$$BC = \sum_{b \in B} u_b{}' * P_{bank} \quad \text{(Eq. (4))}$$

Where:

- $u_b{}'$ is the storage area of asphalt bank b [m²].
- P_{bank} is the price per square metre of land for asphalt bank b [€/m²].

Notably, these costs are excluded from the objective function for the base scenario. Appendix VIII – Model Design Considerations, provides further information regarding the design of this cost calculation.

Eq. (5) defines the raw material costs (RMC):

$$RMC = \sum_{w \in W} \sum_{p \in P} \sum_{t \in T} t^{raw}_{w,p,t} * \left(\begin{matrix} (p_{cr} * pr_{cr}) + (p_{fi} * pr_{fi}) + \\ (p_{sa} * pr_{sa}) + (p_{fl} * pr_{fl}) + (p_{bi} * pr_{bi}) \end{matrix} \right) \Big/ \left((1 + r_{montly})^t \right) \quad \text{(Eq. (5))}$$

Where:

- $t^{raw}_{w,p,t}$ represents the quantity of raw material transported from supplier w to asphalt plant p in month t [m³].
- $pr_{cr}, pr_{fi}, pr_{sa}, pr_{fl}, and\ pr_{bi}$ represent the portion of coarse aggregates, fine aggregates, natural sand, filler, and bitumen in a cubic metre of raw material, respectively. The portion of a material depends on the asphalt mixture produced [%].
- $p_{cr}, p_{fi}, p_{sa}, p_{fl}, and\ p_{bi}$ represent the unit price of coarse aggregates, fine aggregates, natural sand, filler, and bitumen per cubic metre of material, respectively [€/m³].
- $r_{monthly}$ is the monthly inflation rate [%].

Eq. (6) defines the RAP processing costs (RPC):

$$RPC = \sum_{b \in B} \sum_{p \in P} \sum_{t \in T} t^{rap}_{b,p.t} * p_{rap} \Big/ \left((1 + r_{montly})^t \right) \quad \text{(Eq. (6))}$$

Where:

- $t^{rap}_{b,p,t}$ represents the quantity of RAP material transported from the asphalt bank b to asphalt plant p in month t [m³].
- p_{rap} is the price of processing RAP by breaking and sieving it before reuse [€/m³].
- $r_{monthly}$ is the monthly inflation rate [%].

Note: in the base scenario, RAP processing costs are based on the amount of RAP material processed at the asphalt plant, not on the quantity of RAP material transported from the asphalt bank to the plant, as this decision variable is not included in the base scenario.

Additionally, there is a slack factor (sf) for the asphalt production capacity (Eq. (7)):

$$sf = \sum_{p \in P} \sum_{t \in T} spc_{p,t} * f_{penalty} \quad \text{(Eq. (7))}$$

Where:

- $spc_{p,t}$ is the quantity of slack for the asphalt production at asphalt plant p in month t [m³].
- $f_{penalty}$ is a penalty factor [-].

The slack factor accounts for situations where the required asphalt production in a given month exceeds the production capacity, thereby preventing the model from crashing. The model's penalty factor ensures the slack factor works as intended. The penalty factor is adjusted to balance asphalt production across all asphalt plants. If the factor is too low, production becomes uneven, with only one plant handling all the output. Conversely, setting the factor too high leads to excessive fine-tuning of production distribution during the optimisation. These extremes are avoided by calibrating the factor at the threshold where production shifts to include all four asphalt plants.

In the base scenario, there is an additional slack factor for the storage capacity at asphalt plants. Due to the lack of an asphalt bank, the available RAP storage capacity is limited, which can result in model crashes. Therefore, the base scenario has an additional slack storage factor for RAP material, which is not penalised. In practice, using a temporary storage for RAP resolves this problem.

Finally, the MILP model aims to minimise the total costs and the penalty associated with production slack (Eq. (8)):

$$Min\ OF = C + sf \qquad \text{(Eq. (8))}$$

7.2.3 Constraints

The model includes several constraints to ensure realistic and feasible solutions. These constraints are detailed in Eqs. (9)–(34).

1. RAP material that becomes available at maintenance sites must be transported to an asphalt bank:

$$\sum\nolimits_{b \in B} r_{l,b,t}^{top} = R_{top,t,l} \quad \forall l \in L, t \in T \qquad \text{(Eq. (9))}$$

$$\sum\nolimits_{b \in B} r_{l,b,t}^{bin} = R_{bin,t,l} \quad \forall l \in L, t \in T \qquad \text{(Eq. (10))}$$

$$\sum\nolimits_{b \in B} r_{l,b,t}^{base} = R_{base,t,l} \quad \forall l \in L, t \in T \qquad \text{(Eq. (11))}$$

Where:

- $r_{l,b,t}^{top}, r_{l,b,t}^{bin}, and\ r_{l,b,t}^{base}$ represent the quantities of top, bin, and base layer RAP material transported from maintenance site l to asphalt bank b in month t [m^3].
- $R_{top,t,l}, R_{bin,t,l}, and\ R_{base,t,l}$ represent the quantities of RAP material from the top, bin, and base layer available at maintenance site l in month t [m^3].

Note: in the base scenario, $r_{l,p,t}^{top}, r_{l,p,t}^{bin}, and\ r_{l,p,t}^{base}$ represent the quantities of top, bin, and base layer RAP material transported from maintenance site l to asphalt plant p in month t [m^3].

2. The amount of RAP material stored at an asphalt bank cannot exceed its storage capacity:

$$rb_{b,t} \leq u_b \quad \forall b \in B, t \in T \qquad \text{(Eq. (12))}$$

Where:

- $rb_{b,t}$ represents the quantity of RAP material stored in asphalt bank b in month t [m^3].
- u_b is the storage capacity of asphalt bank b [m^3].

Note: in the base scenario, this constraint is not applied as for the other constraints related to the asphalt bank (Eqs. (12)–(16)).

3. An asphalt bank cannot supply more RAP material to asphalt plants than it has stored:

$$\sum_{P \in P} t_{b,p,t}^{rap} \leq rb_{b,t} \quad \forall b \in B, t \in T \qquad \text{(Eq. (13))}$$

Where:

- $t_{b,p,t}^{rap}$ represents the quantity of RAP material transported from the asphalt bank b to asphalt plant p in month t [m³].
- $rb_{b,t}$ represents the quantity of RAP material stored in asphalt bank b in month t [m³].

4. The RAP balance at an asphalt bank must be met every month. The equation that represents this balance is:

$$rb_{b,t} = rb_{b,(t-1)} + \sum_{l \in L} r_{l,b,t}^{top} + \sum_{l \in L} r_{l,b,t}^{bin} + \sum_{l \in L} r_{l,b,t}^{base} - \sum_{p \in P} t_{b,p,t}^{rap} \quad \forall b \in B, t \in T \qquad \text{(Eq. (14))}$$

Where:

- $rb_{b,t}$ represents the quantity of RAP material stored in asphalt bank b in month t [m³].
- $rb_{b,(t-1)}$ represents the quantity of RAP material stored in asphalt bank b at the end of the previous month $t-1$ [m³]. It serves as the starting point for calculating the current month's storage.
- $r_{l,b,t}^{top}, r_{l,b,t}^{bin}, and\ r_{l,b,t}^{base}$ represent the quantities of top, bin, and base layer RAP material transported from maintenance site l to asphalt bank b in month t [m³].
- $t_{b,p,t}^{rap}$ represents the quantity of RAP material transported from the asphalt bank b to asphalt plant p in month t [m³].

The equation as a whole expresses a balance: the RAP material stored in an asphalt bank at the end of a given month ($rb_{b,t}$) is equal to the quantity stored at the end of the previous month ($rb_{b,(t-1)}$) plus any RAP material added from the maintenance site (for different asphalt layers) during the current month, minus any RAP material transported to asphalt plants. That ensures that the inventory is accurately updated each month.

5. Only a single asphalt bank can be selected for utilisation:

$$\sum_{b \in B} bs_b = 1 \qquad \text{(Eq. (15))}$$

Where, bs_b is selected asphalt bank b.

6. The storage capacity of the asphalt bank cannot exceed a maximum capacity:

$$u_b \leq set_{cap} * bs_b \quad \forall b \in B \qquad \text{(Eq. (16))}$$

Where:

- u_b is the storage capacity of asphalt bank b [m³].
- set_{cap} represents the maximum storage capacity the model can set if the bank is selected [m³].
- bs_b indicates whether asphalt bank b is selected; if selected 1, otherwise 0.

7. Asphalt production at an asphalt plant must not exceed its maximum production capacity with additional slack:

$$p_{p,t}^{top} + p_{p,t}^{bin} + p_{p,t}^{base} \leq C_p^{prod} + spc_{p,t} \quad \forall p \in P, t \in T \qquad \text{(Eq. (17))}$$

Where:

- $p_{p,t}^{top}, p_{p,t}^{bin}, and\ p_{p,t}^{base}$ represent the quantities of asphalt produced for the top, bin, and base layers at asphalt plant p in month t [m3].
- C_p^{prod} is the maximum production capacity of asphalt plant p [m3]. It defines the upper limit of asphalt production capacity under normal circumstances.
- $spc_{p,t}$ is a slack variable which allows for additional asphalt production, if necessary, beyond the "normal" maximum capacity [m3]. While using this slack incurs a penalty in the objective function, it helps prevent the model from failing or "crashing" due to overcapacity constraints.

In summary, the total asphalt production for all layers at plant p in month t (i.e., $p_{p,t}^{top} + p_{p,t}^{bin} + p_{p,t}^{base}$) must be less than or equal to the plant's "normal" production capacity (C_p^{prod}), plus any additional capacity provided by the slack variable ($spc_{p,t}$). That ensures that production stays within realistic limits while providing flexibility to handle unexpected demands or variations.

8. The quantity of asphalt produced must equal the sum of the portion of RAP and raw materials processed for each asphalt layer:

$$p_{p,t}^{top} = prp_{p,t}^{top} + prw_{p,t}^{top} \quad \forall p \in P, t \in T \qquad \text{(Eq. (18))}$$

$$p_{p,t}^{bin} = prp_{p,t}^{bin} + prw_{p,t}^{bin} \quad \forall p \in P, t \in T \qquad \text{(Eq. (19))}$$

$$p_{p,t}^{base} = prp_{p,t}^{base} + prw_{p,t}^{base} \quad \forall p \in P, t \in T \qquad \text{(Eq. (20))}$$

Where:

- $p_{p,t}^{top}, p_{p,t}^{bin}, and\ p_{p,t}^{base}$ represent the quantities of asphalt produced for the top, bin, and base layers at asphalt plant p in month t [m3].
- $prp_{p,t}^{top}, prp_{p,t}^{bin}, and\ prp_{p,t}^{base}$ represent the quantities of RAP material processed for the top, bin and base layers at the asphalt plant p in month t [m3].
- $prw_{p,t}^{top}, prw_{p,t}^{bin}, and\ prw_{p,t}^{base}$ represent the quantities of raw material processed for the top, bin, and base layers at the asphalt plant p in month t [m3].

In summary, for each layer of asphalt (top, bin, and base), the total quantity produced at a plant in a given month must equal the sum of RAP material and raw material processed for that layer. That ensures that the production output is balanced correctly with the input materials.

9. The quantity of RAP material used for the production of asphalt is restricted by 30% in top layers and 70% for bin and base layers:

$$prp_{p,t}^{top} \leq 0.30 * p_{p,t}^{top} \quad \forall p \in P, t \in T \qquad \text{(Eq. (21))}$$

$$prp_{p,t}^{bin} \leq 0.70 * p_{p,t}^{bin} \quad \forall p \in P, t \in T \qquad \text{(Eq. (22))}$$

$$prp_{p,t}^{base} \leq 0.70 * p_{p,t}^{base} \quad \forall p \in P, t \in T \qquad \text{(Eq. (23))}$$

Where:

- $prp_{p,t}^{top}, prp_{p,t}^{bin}, and\ prp_{p,t}^{base}$ represent the quantities of RAP material processed for the top, bin and base layers at the asphalt plant p in month t [m3].
- $p_{p,t}^{top}, p_{p,t}^{bin}, and\ p_{p,t}^{base}$ represent the quantities of asphalt produced for the top, bin, and base layers at asphalt plant p in month t [m3], multiplied by the allowed percentage of RAP material per asphalt layer.

10. The amount of RAP material stored at an asphalt plant cannot exceed its storage capacity:

$$s_{p,t}^{rap} \leq C_p^{rap} \quad \forall p \in P, t \in T \qquad \text{(Eq. (24))}$$

Where:

- $s_{p,t}^{rap}$ represents the quantity of RAP material stored at asphalt plant p in month t [m³].
- C_p^{rap} is the storage capacity for RAP material at asphalt plant p [m³].

In the base scenario, this constraint has a slack variable which allows additional storage beyond the "normal" maximum capacity. The slack variable prevents the model from crashing due to minimal RAP storage capacity due to the lack of an asphalt bank. Using this slack does not incur a penalty in the objective function as it does for using the production slack factor. However, storing RAP material in this "additional" storage incurs extra handling costs, as presented by the green factor in Eq. (3). These extra costs are for the extra handling for unloading and loading RAP material temporarily stored at a construction site pending storage options at the asphalt plant due to lack of storage capacity.

11. The amount of raw material stored at an asphalt plant cannot exceed its storage capacity:

$$s_{p,t}^{raw} \leq C_p^{raw} \quad \forall p \in P, t \in T \qquad \text{(Eq. (25))}$$

Where:

- $s_{p,t}^{raw}$ represents the quantity of raw material stored at asphalt plant p in month t [m³].
- C_p^{raw} is the storage capacity for raw material at asphalt plant p [m³].

12. The storage of RAP material at an asphalt plant is managed from month to month. The equation that represents this balance is:

$$s_{p,t}^{rap} = s_{p,(t-1)}^{rap} + \sum_{b \in B} t_{b,p,t}^{rap} - prp_{p,t}^{top} - prp_{p,t}^{bin} - prp_{p,t}^{base} \quad \forall p \in P, t \in T \qquad \text{(Eq. (26))}$$

Where:

- $s_{p,t}^{rap}$ represents the quantity of RAP material stored at asphalt plant p in month t [m³].
- $s_{p,(t-1)}^{rap}$ represents the quality of RAP material stored at asphalt plant p at the end of the previous month $t-1$ [m³]. It serves as the starting point for calculating the current month's storage.
- $t_{b,p,t}^{rap}$ represents the quantity of RAP material transported from the asphalt bank b to asphalt plant p in month t [m³].
- $prp_{p,t}^{top}, prp_{p,t}^{bin}, and\ prp_{p,t}^{base}$ represent the quantities of RAP material processed for the top, bin and base layers at the asphalt plant p in month t [m³].

The equation as a whole expresses a balance similar to Eq. (14). Notably, in the base scenario, $t_{b,p,t}^{rap}$ is represented by $r_{l,p,t}^{top}, r_{l,p,t}^{bin}, and\ r_{l,p,t}^{base}$ as RAP material is directly transported from maintenance location l to asphalt plant p as the asphalt bank is not existent.

13. The balance of raw materials stored at an asphalt bank must be met every month:

$$s_{p,t}^{raw} = s_{p,(t-1)}^{raw} + \sum_{b \in B} t_{w,p,t}^{raw} - prw_{p,t}^{top} - prw_{p,t}^{bin} - prw_{p,t}^{base} \quad \forall p \in P, t \in T \qquad \text{(Eq. (27))}$$

Where:

- $s_{p,t}^{raw}$ represents the quantity of raw material stored at asphalt plant p in month t [m3].
- $s_{p,(t-1)}^{raw}$ represents the quantity of raw material stored at asphalt plant p at the end of the previous month $t-1$ [m3]. It serves as the starting point for calculating the current month's storage.
- $t_{w,p,t}^{raw}$ represents the quantity of raw material transported from supplier w to asphalt plant p in month t [m3].
- $prw_{p,t}^{top}, prw_{p,t}^{bin}, and\ prw_{p,t}^{base}$ represent the quantities of raw material processed for the top, bin, and base layers at the asphalt plant p in month t [m3].

The equation as a whole expresses a balance similar to Eq. (14) and Eq. (26).

14. The asphalt production must equal the required asphalt in the maintenance zones. The asphalt production must, thus, equal the transport of asphalt to these maintenance zones:

$$\sum_{z \in Z} t_{p,z,t}^{top} = p_{p,t}^{top} \quad \forall p \in P, t \in T \qquad \text{(Eq. (28))}$$

$$\sum_{z \in Z} t_{p,z,t}^{bin} = p_{p,t}^{bin} \quad \forall p \in P, t \in T \qquad \text{(Eq. (29))}$$

$$\sum_{z \in Z} t_{p,z,t}^{base} = p_{p,t}^{base} \quad \forall p \in P, t \in T \qquad \text{(Eq. (30))}$$

Where:

- $t_{p,z,t}^{top}, t_{p,z,t}^{bin}, and\ t_{p,z,t}^{base}$ represent the quantities of top, bin, and base layer asphalt types transported from asphalt plant p to maintenance zone z in month t [m3].
- $p_{p,t}^{top}, p_{p,t}^{bin}, and\ p_{p,t}^{base}$ represent the quantities of asphalt produced for the top, bin, and base layers at asphalt plant p in month t [m3].

15. Only a single asphalt plant can transport asphalt to a maintenance zone:

$$\sum\nolimits_{p \in P} ps_{p,z,t} = 1 \quad \forall z \in Z, t \in T \qquad \text{(Eq. (31))}$$

Here, $ps_{p,z,t}$ represents the selected asphalt plant p for maintenance zone z in month t.

16. Only the tender-winning asphalt plant can supply the associated maintenance zone. In other words, this constraint ensures the selected asphalt plant (i.e., the plant that won the tender) transports asphalt to the specified maintenance zone:

$$t_{p,z,t}^{top} = ps_{p,z,t} * R_{top,t,z} \quad \forall z \in\ Z, p \in P, t \in T \qquad \text{(Eq. (32))}$$

$$t_{p,z,t}^{bin} = ps_{p,z,t} * R_{bin,t,z} \quad \forall z \in\ Z, p \in P, t \in T \qquad \text{(Eq. (33))}$$

$$t_{p,z,t}^{base} = ps_{p,z,t} * R_{base,t,z} \quad \forall z \in\ Z, p \in P, t \in T \qquad \text{(Eq. (34))}$$

Where:

- $t_{p,z,t}^{top}, t_{p,z,t}^{bin}, and\ t_{p,z,t}^{base}$ represent the quantities of top, bin, and base layer asphalt types transported from asphalt plant p to maintenance zone z in month t [m3].
- $ps_{p,z,t}$ represents the selected asphalt plant p for maintenance zone z in month t.
- $R_{top,t,z}, R_{bin,t,z}, and\ R_{base,t,z}$ represent the quantities of top, bin, and base layer asphalt types required at maintenance zone z in month t [m3].

7.3 Case Studies and Sensitivity Analysis

This research explores three case studies: (1) the standard scenario with an asphalt bank, (2) a future scenario with an asphalt bank, and (3) the standard scenario with multiple asphalt banks. In case study 1, the standard scenario is compared to the baseline, representing the asphalt supply chain without an asphalt bank. The other two case studies are then compared to the standard scenario from the first case study.

The model used for these case studies includes various adjustable parameters, allowing for robustness testing and sensitivity analysis. The model's objective in the case studies and sensitivity analysis is to minimise the total costs within the asphalt supply chain. However, the method for calculating these costs differs slightly between the baseline and the asphalt bank scenarios, as explained in section 7.2.2, Model Objective. The main difference is the inclusion or exclusion of the asphalt bank(s) within the supply chain.

The asphalt bank scenario considers five cost components: transport cost, handling cost, land-use cost, raw material cost, and RAP processing cost. In contrast, the baseline accounts for only four cost components: transport, handling, raw material, and RAP processing. Additionally, the asphalt bank scenario optimises the location of the asphalt bank, further distinguishing it from the baseline.

The following subsections outline the design of the three case studies – the standard, future, and multiple asphalt bank scenarios – and explain the planned sensitivity analysis. The results of the model simulations, including the case studies and the sensitivity analysis, are presented in Chapter 8, Results of Model Simulations: Case Studies and Sensitivity Analysis.

Table 7.11 and Table 7.12 provide an overview of the case study scenarios and sensitivity analysis, respectively, including the relevant model settings. The scenarios are based on the model framework discussed in Appendix VIII – Model Design Considerations; the relevant model settings are discussed in the tables.

Table 7.11: Overview of the Case Study Scenarios.

Case	Scenario	Settings
Case Study 1	Asphalt bank scenario	• **SINGLE** asphalt bank permitted. • **100%** of the road sections within the maintenance window require an asphalt surface layer replacement.† • **30%** of the road sections within the maintenance window require an asphalt binder layer replacement. • **10%** of the road sections within the maintenance window require an asphalt base layer replacement. • The permitted recycling percentage in the asphalt surface layer is **30%** and **70%** for the asphalt binder and base layers. *Compared to the baseline.* *(Asphalt supply chain without an asphalt bank)*

† Section 7.3.1, Case Study 1: The Current Asphalt Supply Chain With and Without an Asphalt Bank, explains the road maintenance procedure.

Case Study 2	**Asphalt bank future scenario**	• **SINGLE** asphalt bank permitted. • **100%** of the road sections within the maintenance window require an asphalt surface layer replacement. • **50%** of the road sections within the maintenance window require an asphalt binder layer replacement. • **50%** of the road sections within the maintenance window require an asphalt base layer replacement. • The permitted recycling percentage in the asphalt surface layer is **65%** and **70%** for the asphalt binder and base layers. *Compared to Case Study 1.* *(Asphalt bank scenario)*
Case Study 3	Multiple asphalt bank scenario	• **MULTIPLE** asphalt banks permitted. • **100%** of the road sections within the maintenance window require an asphalt surface layer replacement. • **30%** of the road sections within the maintenance window require an asphalt binder layer replacement. • **10%** of the road sections within the maintenance window require an asphalt base layer replacement. • The permitted recycling percentage in the asphalt surface layer is **30%** and **70%** for the asphalt binder and base layers. *Compared to Case Study 1.* *(Asphalt bank scenario)*

Table 7.12: Overview of the Sensitivity Analysis.

Case	Scenario	Settings
Sensitivity Analysis (1)	Low supply – high demand scenario	• **20%** of the calculated RAP volume is supplied to the asphalt bank (low supply).‡ • **80%** of the calculated RAP volume is demanded as required asphalt volume (high demand). • Resulting in a supply-demand ratio of **1:4**.
	High supply – low demand scenario	• **60%** of the calculated RAP volume is supplied to the asphalt bank (high supply). • **40%** of the calculated RAP volume is demanded as required asphalt volume (low demand). • Resulting in a supply-demand ratio of **3:2**.
Sensitivity Analysis (2)	Low recycling rate scenario	• The permitted recycling percentage in the asphalt surface layer is **30%** and **50%** for the asphalt binder and base layers.
	High recycling rate scenario	• The permitted recycling percentage in the asphalt surface layer is **65%** and **90%** for the asphalt binder and base layers.

‡ Section 7.3.4, Sensitivity Analysis of the Asphalt Supply Chain With an Asphalt Bank, explains the RAP volume calculations.

7.3.1 Case Study 1: The Current Asphalt Supply Chain With and Without an Asphalt Bank

The first case study simulates the standard asphalt bank scenario compared to the baseline – the asphalt supply chain without an asphalt bank – to examine the effect of an asphalt bank on the spatial and temporal dynamics of RAP and the total costs of the asphalt supply chain in the Amsterdam Transport Region. The standard asphalt bank scenario only deviates from the baseline by considering an asphalt bank in the supply chain.

The input data is standard for this case study and is consistent with the model design considerations discussed in Appendix VIII – Model Design Considerations. Nevertheless, because the results of Case Studies 2 and 3 are compared to Case Study 1, it is important to highlight several parameters. The following parameters are noteworthy to highlight:

- **Application and optimisation asphalt bank**: The simulated asphalt supply chain is limited to a single asphalt bank.
- **Release of RAP (Reclaimed Asphalt Pavement) material from the asphalt surface layer**: 100% of the road sections within the maintenance window require an asphalt surface layer replacement. *See more information about the "road maintenance procedure" beneath this enumeration.*
- **Release of RAP material from the asphalt binder layer**: 30% of the road sections within the maintenance window require an asphalt binder layer replacement, a percentage derived from the interviews.
- **Release of RAP material from the asphalt base layer**: 10% of the road sections within the maintenance window require an asphalt base layer replacement, a percentage based on the interviews and discussions with Ballast Nedam Road Specialities.
- **Reuse Rates**: The permitted percentage of recycling in the asphalt surface layer is 30% and 70% for the asphalt binder and base layers. These rates reflect current regulations for surface layers and practical applications in binder and base layers.

Explanation: Road Section Maintenance Requirements
The process by which the model determines the maintenance requirements for a road section's surface, binder, and base layer needs further clarification. The model first checks whether a road section is due for maintenance by considering the construction date and the average lifespan of the asphalt surface layer. If the surface layer requires first-time maintenance, the binder and base layers typically do not. According to the interviews, the second or third surface layer replacement generally coincides with the first binder layer replacement.

The model reflects this by the assumption that for every three road sections needing surface layer maintenance, one (about 30%) will also require a binder layer replacement. Similarly, for every ten road sections, one will require a base layer replacement (10%). Additionally, the model accounts for the fact that replacing the base layer requires removing the binder and surface layers, which is considered in the model's calculations.

As stated before, Appendix VIII – Model Design Considerations provides more detailed information on the standard input data and model parameters. Any deviations from the descriptions in this appendix are noted throughout this report.

7.3.2 Case Study 2: The Future Asphalt Supply Chain With an Asphalt Bank

The second case study simulates the future asphalt bank scenario compared to Case Study 1 – the standard asphalt bank scenario – to study how a different supply chain "climate" affects the asphalt bank, the spatial and temporal dynamics of RAP, and the total costs of the asphalt supply chain in the Amsterdam Transport Region. The scenario in this case study differs from Case Study 1 as the future asphalt bank scenario has different model parameters concerning material release and reuse rates, as shown below.

The input data for this case study – the future asphalt supply chain with an asphalt bank – deviates from Case Study 1 and the model framework discussed in Appendix VIII – Model Design Considerations. Case Study 2 represents the future asphalt supply chain with an asphalt bank, in which the asphalt industry wants to apply 65% recycling in the asphalt surface layer, and maintenance of binder and base layers increases. The following parameters, similar to those discussed in section 7.3.1, Case Study 1: The Current Asphalt Supply Chain With and Without an Asphalt Bank, are noteworthy to highlight:

- **Application and optimisation asphalt bank**: The simulated asphalt supply chain is limited to a single asphalt bank.
- **Release of RAP material from the asphalt surface layer**: 100% of the road sections within the maintenance window require an asphalt surface layer replacement. *See more information about the "road maintenance procedure" in Case Study 1.*
- **Release of RAP material from the asphalt binder layer**: 50% of the road sections within the maintenance window require an asphalt binder layer replacement, a percentage based on the fact that removing 50% of the base layers also demands the removal of 50% of the binder layers.
- **Release of RAP material from the asphalt base layer**: 50% of the road sections within the maintenance window require an asphalt base layer replacement. (Chapter 6, Patterns of the Current Asphalt Market), where current practices typically overlay the old base layer, the future will require significant base layer maintenance. This configuration explores the model's response to this future perspective.
- **Reuse rates**: The permitted percentage of recycling in the surface layer is 65% and 70% for the binder and base layers. This configuration aligns with the future vision of recycling, where the asphalt bank plays a central role in achieving 65% reuse in surface layers, which requires high-quality pre-processed RAP.

Beyond these parameters, there are no further deviations from the default model settings, as detailed in Appendix VIII – Model Design Considerations.

7.3.3 Case Study 3: The Current Asphalt Supply Chain With Multiple Asphalt Banks

The third case study simulates the current asphalt supply chain with multiple asphalt banks compared to Case Study 1 – the standard scenario with a single asphalt bank – to study what the model finds an optimal number of asphalt banks and how this affects the spatial and temporal dynamics of RAP and the total costs of the asphalt supply chain in the Amsterdam Transport Region. In this case study, the model has complete flexibility to optimise the number and location of asphalt banks for the current asphalt supply chain, with the only constraint being the number of available locations for an asphalt bank.

The input data for this case study deviates from Case Study 1 and the model framework discussed in Appendix VIII – Model Design Considerations. Case Study 3 represents the current asphalt supply chain with multiple asphalt banks, varying from Case Study 1, as there is no constraint on the maximum number of asphalt banks. The following parameters, similar to those discussed in section 7.3.1, Case Study 1: The Current Asphalt Supply Chain With and Without an Asphalt Bank, are noteworthy to highlight:

- **Application and optimisation asphalt bank**: The simulated asphalt supply chain is NOT limited to a maximum number of asphalt banks.
- **Release of RAP material from the asphalt surface layer**: 100% of the road sections within the maintenance window require an asphalt surface layer replacement. *See more information about the "road maintenance procedure" in Case Study 1.*
- **Release of RAP material from the asphalt binder layer**: 30% of the road sections within the maintenance window require an asphalt binder layer replacement, a percentage derived from the interviews.
- **Release of RAP material from the asphalt base layer**: 10% of the road sections within the maintenance window require an asphalt base layer replacement, a percentage based on the interviews and discussions with Ballast Nedam Road Specialities.
- **Reuse rates**: The permitted percentage of recycling in the asphalt surface layer is 30% and 70% for the asphalt binder and base layers. These rates reflect current regulations for surface layers and practical applications in binder and base layers.

Beyond these parameters, there are no further deviations from the default model settings, as detailed in Appendix VIII – Model Design Considerations.

7.3.4 Sensitivity Analysis of the Asphalt Supply Chain With an Asphalt Bank

This section delves into the sensitivity analysis for the asphalt bank scenario, focusing on the impact of two key factors. While the analysis may offer further insight into the three previous case studies, its primary aim is to explore the model's robustness and examine how particular parameters influence the asphalt bank and RAP's spatial and temporal dynamics.

The sensitivity analysis is centred exclusively on the asphalt bank scenario, as this is the focal point of the research. The foundation of this analysis is the asphalt supply chain, which incorporates the asphalt bank, as described in Case Study 1. The analysis targets two critical aspects: the RAP inflow and asphalt demand (supply and demand) and the recycling rates.

Although there are other potential factors or scenarios to explore, this study focuses on these two elements because they directly relate to the asphalt bank and its market situation. The emphasis of this study is to understand the spatial and temporal dynamics of RAP and how an asphalt bank influences these dynamics. While economic factors and asphalt mixture variations could also affect model outcomes, they are excluded from this sensitivity analysis to maintain a clear focus on the asphalt bank and its material flows.

The following subsections overview the two sensitivity analyses and their design. Paragraph 8.4, Sensitivity Analysis of the Asphalt Supply Chain With an Asphalt Bank , presents the results of these sensitivity analyses.

7.3.4.1 RAP Availability and Asphalt Demand

The first sensitivity analysis examines the relationship between the availability of RAP for reuse and the demand for asphalt. The focus is on how significant imbalances between RAP availability and asphalt demand affect the model's outcomes.

The basis for this analysis is Case Study 1, as detailed in Appendix VIII – Model Design Considerations. Four different situations are simulated by varying two key parameters: the "loss factor" (default 20%) and the "new construction factor" (default 115%) – see more information below. These parameters reflect the loss in RAP availability and the additional demand for asphalt in new construction projects. The sensitivity analysis investigates how these imbalances affect the flow of materials at the asphalt bank.

> **Explanation: "Loss" and "New Construction" Factors**
> When a road section falls within the maintenance window, the theoretical volume of RAP material released and asphalt required for replacement is calculated by the model, multiplying the road surface area by the thickness of the asphalt layer. However, the model has to account for material losses and new road construction projects. Therefore, the model applies a loss factor to the volume of RAP released and a new road construction factor to the asphalt volume required.
>
> The model accounts for material losses by multiplying the theoretical volume by a factor like 0.8, meaning 20% of the RAP material is lost, and only 80% is effectively available for reuse. New road construction projects are accounted for by multiplying the theoretical volume by the factor 1.15, meaning 115% asphalt is required; in other words, 15% extra asphalt for new road construction projects. The 20% loss factor is based on literature indicating that approximately 20% of asphalt released cannot be reused.
>
> In the sensitivity analysis, these factors are "creatively" used to simulate different scenarios. The loss factor is set to 0.2 (indicating 20% material use and 80% loss), and the new construction factor is set to 0.8 to simulate supply shortages and abundance. Simulating a 1:4 supply-demand ratio and a 3:2 supply-demand ratio and compare them.

Two of the four simulated situations, the most extreme scenarios, are compared:

1. 20% supply (80% loss) and 80% demand.
2. 60% supply (40% loss) and 40% demand.

Section 8.4.1, RAP Availability and Asphalt Demand, presents the results of this scenario analysis.

7.3.4.2 Asphalt Recycling Rates

The second sensitivity analysis focuses on the allowed recycling rates of RAP material in new asphalt mixtures. The sensitivity analysis explores how varying the recycling rates impacts the flow of RAP material through the asphalt bank and consequently affects the RAP's spatial and temporal dynamics.

The basis for this analysis is Case Study 1, as described in Appendix VIII – Model Design Considerations. Four situations are simulated, each with different allowed recycling percentages for the asphalt surface, binder, and base layers. While these adjustments do not change the overall supply of RAP or asphalt demand, they affect the flow rate of RAP through the asphalt bank.

Two of the four simulated scenarios, the most extreme scenarios, are compared:

1. 30% surface layer / 50% binder layer / 50% base layer.
2. 65% surface layer / 90% binder layer / 90% base layer.

The reason for not considering 100% recycling in the binder and base layers is that, in practice, this percentage is not achieved solely with RAP material. A significant part is ECO-granulate, which is thermally cleaned RAP material. This research only considers clean RAP material, which results in a maximum RAP reuse percentage of 90%.

Section 8.4.2, Asphalt Recycling Rates, presents the results of this scenario analysis.

7.4 Conclusion

The chapter provides a comprehensive overview of the model's framework, mathematical underpinnings, and the case studies and sensitivity analyses to be conducted. The detailed exploration of the model design, supported by mathematical formulations and strategic case study selection, ensures a robust foundation for understanding and evaluating the asphalt supply chain scenarios. The chapter outlines the key components and objectives of the model but also systematically justifies the choices made, offering a clear and well-substantiated pathway for the model simulations and sensitivity analyses that follow. This structured approach establishes a coherent narrative that ties together the theoretical considerations, practical implications, and anticipated outcomes, setting the stage for the detailed results and insights presented in the next chapter.

8 Results of Model Simulations: Case Studies and Sensitivity Analysis

This chapter presents an in-depth exploration of the current and future asphalt supply chain chains, focusing on the potential impact of an asphalt bank on the economic aspects and the spatial and temporal dynamics of Reclaimed Asphalt Pavement (RAP). Through three detailed case studies and several sensitivity analyses, the chapter examines the difference between supply chain scenarios with and without an asphalt bank and the implications of factors such as RAP availability, asphalt demand, and recycling rates. The findings offer valuable insights into the optimisation of asphalt supply chains and the role of asphalt banks in cost efficiency and sustainability.

The chapter is structured as follows:

- **Paragraph 8.1 Case Study 1: The Current Asphalt Supply Chain With and Without an Asphalt Bank** – This section provides a comprehensive insight into the current asphalt supply chain, comparing scenarios with and without an asphalt bank. It discusses the economic impacts, the distribution and storage of RAP, and the variations in asphalt production between the two scenarios.
- **Paragraph 8.2 Case Study 2: The Current and Future Asphalt Supply Chain With an Asphalt Bank** – This section explores the future of the asphalt supply chain by comparing the current scenario with an asphalt bank to a future scenario that envisions increased recycling rates in asphalt production. The analysis focuses on the resulting cost implications and the necessity of an asphalt bank to meet future recycling targets.
- **Paragraph 8.3 Case Study 3: The Current Asphalt Supply Chain With Multiple Asphalt Banks** – This section examines the current supply chain with multiple asphalt banks compared to the current scenario with a single asphalt bank. The analysis focuses on the resulting cost implications and the impact on RAP's spatial and temporal dynamics.
- **Paragraph 8.4 Sensitivity Analysis of the Asphalt Supply Chain With an Asphalt Bank** – This section presents two sensitivity analyses to test the model's robustness and explore the effects of various parameters on the asphalt supply chain. The analyses cover the impact of varying RAP supply and asphalt demand and the influence of different recycling rates on the supply chain dynamics.
- **Paragraph 8.5 Summary of the Findings** – This section summarises the key findings of the case studies and sensitivity analysis before finishing the chapter with the chapter's conclusion.
- **Paragraph 8.6 Conclusion** – The chapter concludes with the key findings of the case studies and sensitivity analysis, highlighting the significance of asphalt banks and their effect on the asphalt supply chain.

8.1 Case Study 1: The Current Asphalt Supply Chain With and Without an Asphalt Bank

The simulation of Case Study 1, representing the current state of the asphalt supply chain, offers insight into the impact of an asphalt bank on the economic aspects of the asphalt supply chain and the spatial and temporal dynamics of RAP. This section highlights the key results and discusses the main differences between the baseline and asphalt bank scenarios regarding supply chain economics and the distribution of RAP.

Figure 8.1 compares the total costs and RAP and raw material usage in the asphalt supply chain for the scenario with and without an asphalt bank. Several points are noteworthy, particularly the differences in total costs and RAP and raw material usage.

Figure 8.1: Comparing Supply Chain Cost and Raw Material Usage for the Current Supply Chain With and Without an Asphalt Bank.

Total Supply Chain Cost Analysis

The primary difference in the total supply chain costs arises from the acquisition of the asphalt bank, which amounts to €6,894,124. Additionally, transport costs are €1,119,167 higher, handling costs increase by €1,385,336 raw material costs rise by €970,090, and RAP pre-processing expenses rise by €593,209. Consequently, the total costs in the asphalt supply chain with the asphalt bank over five years are €4,067,802 higher than those of the current supply chain without an asphalt bank, considering the acquisition of the asphalt bank €10,961,926 higher.

An increase in overall costs was anticipated with the introduction of an asphalt bank, primarily due to the costs of the asphalt bank itself and increased transport and handling of RAP at the bank. However, the rise in raw material costs was unexpected, though explainable in hindsight, see heading Raw Material Usage.

The difference in the raw material costs is the same in percentage terms, but the more expensive raw material or larger fraction contributes more to the total cost increase. The largest disparities are due to coarse aggregate and bitumen, with the other raw materials contributing little to the overall difference. Over time, material cost deviations are minimal, with only slight variations observed. When costs are incurred, the peaks in the asphalt bank scenario are higher than those in the base scenario, which aligns with the overall cost pattern.

Raw Material Usage

The higher raw material costs are due to lower recycling rates in the asphalt bank scenario and, thus, the extra required raw materials. The scenario without an asphalt bank, the current asphalt supply chain scenario, adheres to the permitted recycling rates - 30% for surface layers and 70% for binder and base layers. In contrast, the asphalt bank scenario shows recycling rates of 28.5% for surface layers, 65.6% for binder layers, and 70% for base layers.

The higher recycling rates in the base scenario can be attributed to two factors. Firstly, in the base scenario, RAP material is transported directly from the maintenance site to the asphalt plant. While the RAP material requires pre-processing at the plant, which incurs some costs, it remains a cheaper alternative compared to purchasing, transporting, and handling raw materials. Secondly, when the RAP storage at the asphalt plants is full, unused RAP material must be stored at "temporary storage facilities" at the maintenance sites, leading to extra handling costs. The model seeks to minimise these additional costs to keep overall supply chain expenses low, driving the maximisation of RAP reuse in the base scenario.

In the asphalt bank scenario, the model identifies an optimal balance where, after a certain point, the cost savings from reducing raw material and asphalt bank expenses no longer outweigh the costs of transporting, handling, and pre-processing RAP material. Essentially, it becomes more cost-effective to expand the asphalt bank and purchase additional raw materials rather than to continue transporting, handling, and processing RAP material. That explains why the recycling percentages remain slightly below the maximum allowable limit.

The following two subsections provide additional information on the spatial and temporal distribution of RAP and raw material and some interesting observations on asphalt production for the two supply chain scenarios.

8.1.1 Spatial and Temporal Distribution of RAP and Raw Material

A detailed investigation of the spatial and temporal distribution of RAP and the storage of RAP in both scenarios reveals some substantial information. In the asphalt bank scenario, a significant portion of RAP is stored in Asphalt Bank 67 (the asphalt bank number indicates the ID of the asphalt bank location in the dataset), which has a storage capacity of 164,181 m^3. Located on the De Hemmes industrial terrain in Zaandam, the asphalt bank's location is shown in Figure 8.2. Figure 8.3 shows the storage levels at this asphalt bank over time. RAP not stored in the asphalt bank is kept locally at the asphalt plants, with storage levels over time shown in Figure 8.4.

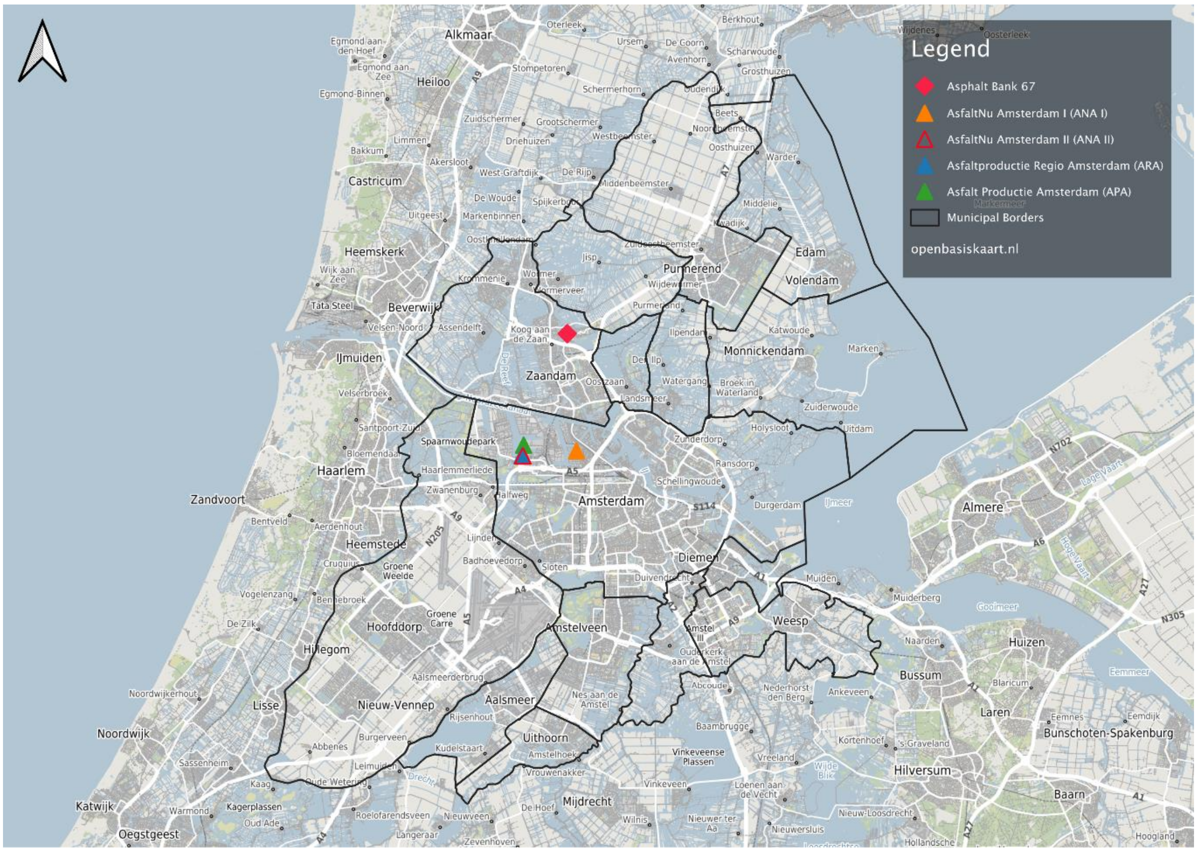

Figure 8.2: Location Candidate Asphalt Bank (67) in the Current Asphalt Supply Chain.

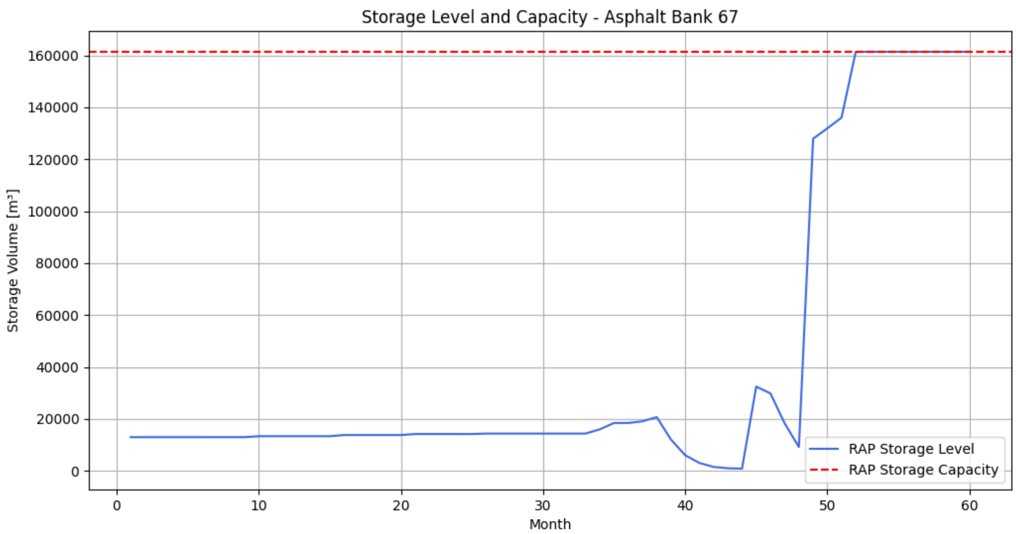

Figure 8.3: Storage Level and Capacity Asphalt Bank (67) in the Current Asphalt Supply Chain.

In contrast, the base scenario presents a different picture regarding the spatial and temporal dynamics of RAP and RAP storage, as illustrated in Figure 8.4. A noteworthy point regarding this scenario concerns the storage capacity at the asphalt plants, which is the only storage option available. In the base scenario, the model permits exceeding the asphalt plant's storage capacity. In practice, this excess RAP material is stored temporarily on the construction site till the relevant asphalt plant has storage capacity available. The model, however, integrates the temporary storage at the construction sites with the asphalt plant's standard storage capacity, using a slack decision variable. As a result, the storage capacity at the asphalt plants can be exceeded by the amount of RAP stored at the construction sites, which account for 33,482 m³ at the APA, 30,153 m³ at the ARA, 40,358 m³ at ANA I, and 34,782 m³ at ANA II - see Figure 8.7 for the RAP storage levels of the temporary storage facilities.

An important detail is that while storing RAP at temporary storage facilities on construction sites is free - meaning no payment for storage is required - there are still additional costs with this type of storage compared to storing the RAP material at the asphalt plant. These costs primarily come from handling, especially reloading RAP for transport from the temporary storage facility to the asphalt plant. These extra handling costs are accounted for in the model.

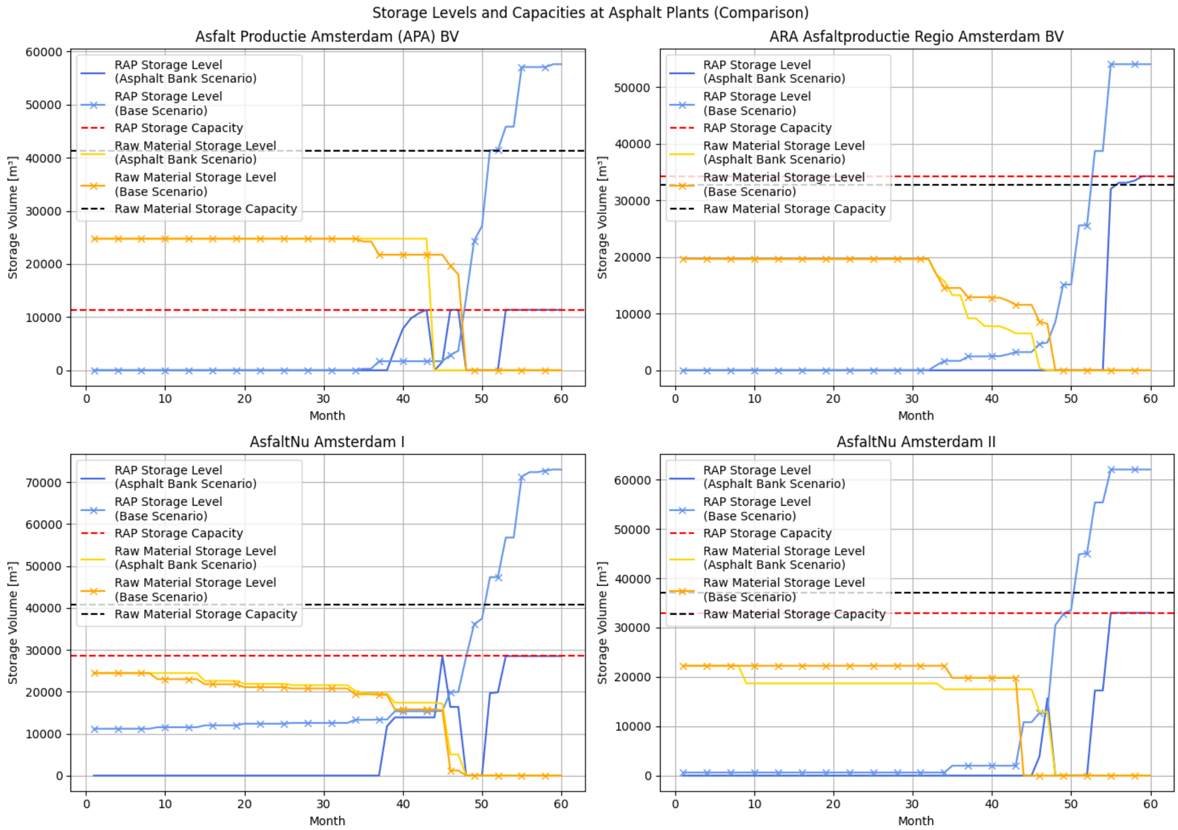

Figure 8.4: Comparison of Storage Levels and Capacities Asphalt Plants for the Current Supply Chain With and Without an Asphalt Bank.

Lastly, it is relevant to note that the raw material storage (see Figure 8.4) gradually decreases over the model's timeline in both scenarios. At the start of the simulation, the raw material storage level is at 60%, as the results represent a snapshot of an ongoing process. Over time, raw materials are consumed for asphalt production, causing the storage levels to decline. Occasionally, small amounts of raw materials are delivered to the asphalt plants. However, since the model aims to minimise costs and does not account for potential asphalt production beyond the 5 years captured in the snapshot, the raw material storage eventually reaches zero.

8.1.2 The Production of Asphalt

A detailed comparison of the asphalt plant production data from both scenarios reveals several noteworthy points. While the overall variation between the production data is not drastic, some differences are worth discussing. To illustrate the relevant points, two of the four asphalt plants are used as examples: ARA Asfaltproductie Regio Amsterdam BV and Asfalt Productie Amsterdam (APA) BV. These two plants are highlighted because they show more pronounced differences between the scenarios, while the other two asphalt plants exhibit minimal variation.

One of the most striking observations is the difference in production between the two scenarios. In the asphalt bank scenario, ARA produces approximately 150,000 m³ of asphalt, whereas in the base scenario, its production increases to around 250,000 m³. Conversely, APA's production is higher in the asphalt bank scenario (~280,000 m³) and lower in the base scenario (~180,000 m³). That suggests that these two plants, in a sense, exchange the production of around 100,000 m³ of asphalt between the two scenarios.

Another noticeable difference is the significantly higher inflow of RAP at ARA in the base scenario, which can be attributed to the absence of an asphalt bank and the generally larger asphalt production volumes for this asphalt plant in this scenario.

Moreover, Figure 8.5 and Figure 8.6 further illustrate that in the asphalt bank scenario, the intake of RAP and raw material is either equal or skewed towards raw materials. In contrast, in the base scenario, the intake of RAP consistently exceeds that of raw materials again due to the absence of an asphalt bank.

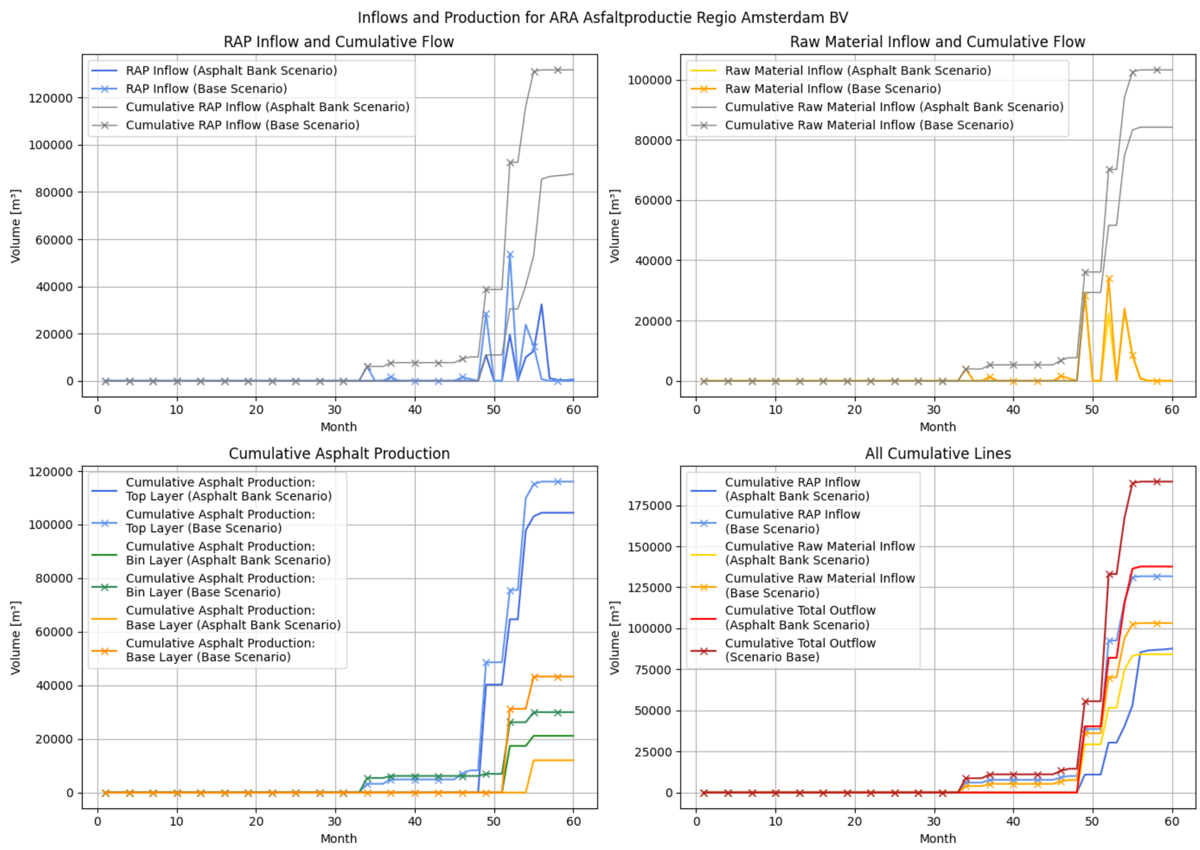

Figure 8.5: Comparison of Asphalt Production ARA for the Current Supply Chain With and Without an Asphalt Bank.

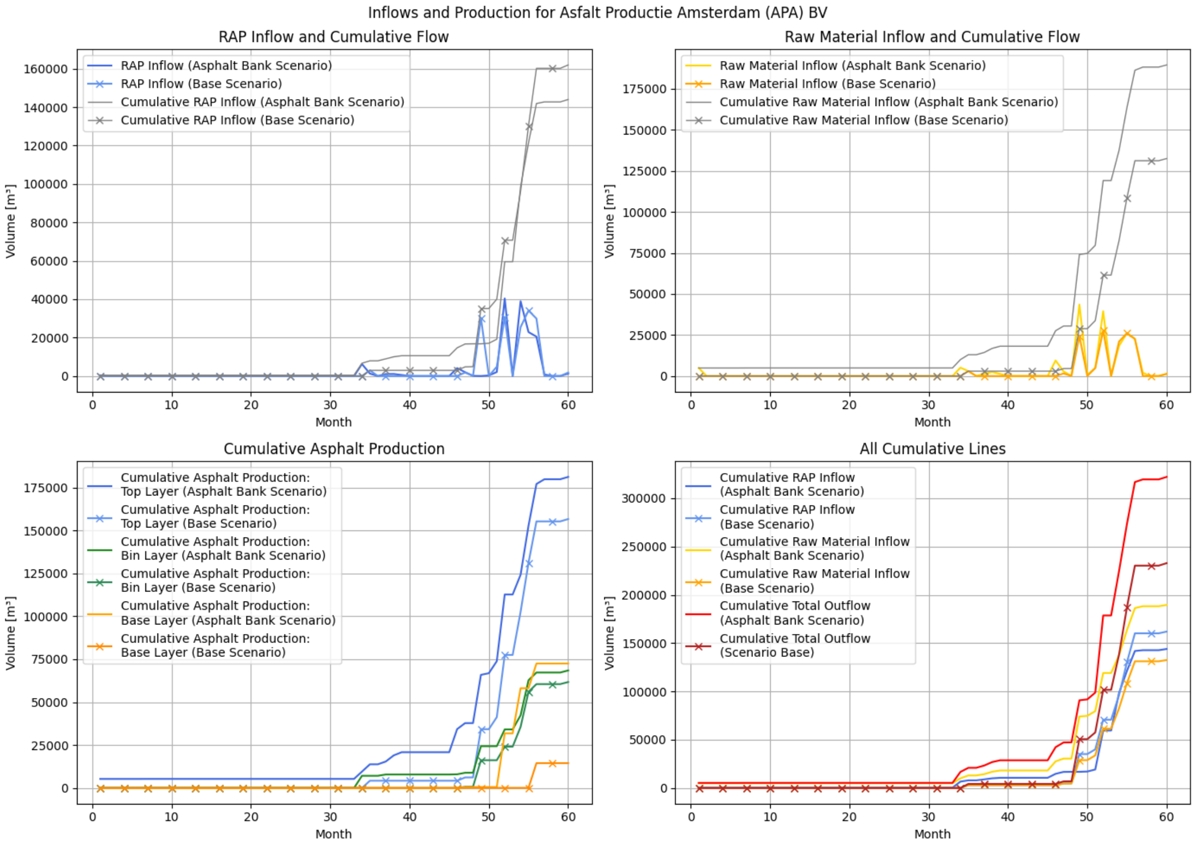

Figure 8.6: Comparison of Asphalt Production APA for the Current Supply Chain With and Without an Asphalt Bank.

Lastly, Figure 8.7 provides insight into the additional asphalt production required and the extra storage capacity needed for RAP. Additional RAP storage capacity is only necessary in the base scenario, as the asphalt bank scenario absorbs this need through the asphalt bank. The figure also highlights the fluctuations in production quantities between APA and ARA, showing that asphalt production is exchanged between these two asphalt plants across the scenarios. The overproduction peaks shift between these plants, underscoring the redistribution of production responsibilities.

In summary, asphalt production and RAP storage slack are managed typically through temporary storage facilities, careful production and maintenance planning, and the potential utilisation of production capacity outside the study region.

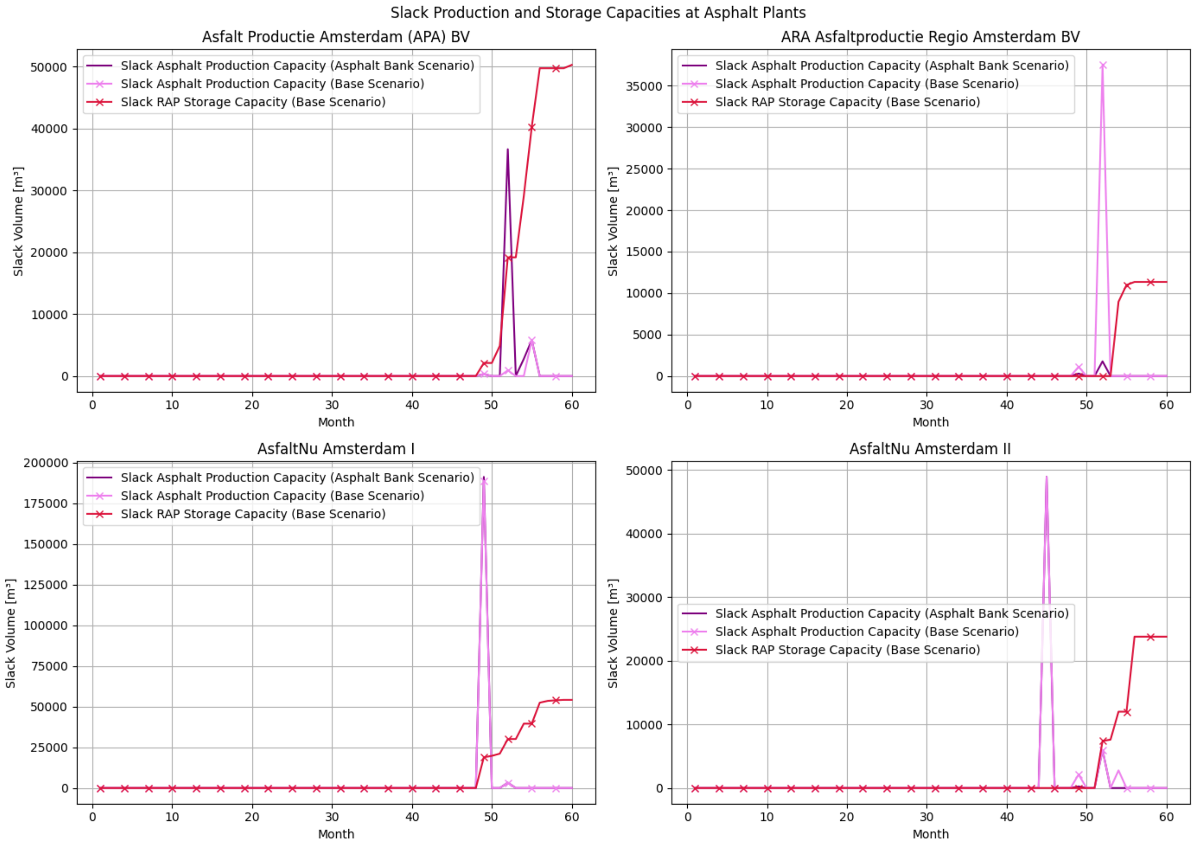

Figure 8.7: Comparison of Slack Asphalt Production and RAP Storage Capacity for the Current Supply Chain With and Without an Asphalt Bank.

8.2 Case Study 2: The Current and Future Asphalt Supply Chain With an Asphalt Bank

The simulation of Case Study 2, representing the envisioned future asphalt supply chain with asphalt banks, aims to provide insight into the economic aspects of the asphalt supply chain and the spatial and temporal dynamics of RAP in the future scenario. This section presents the main results and discusses the difference between Case Study 1 and the future scenario of Case Study 2.

It is important to note why this comparison focuses only on the asphalt supply chain with an asphalt bank rather than including the base scenario. In the future scenario, the recycling percentage in the asphalt surface layer will increase from 30% to 65%. Achieving this 65% recycling rate requires an asphalt bank or a similar RAP processing facility, partly due to traffic safety considerations that necessitate better quality control of RAP at higher recycling percentages in asphalt surface layers. The anticipated need for an asphalt bank in this future scenario is a significant driver for this research, making it illogical to compare the base scenario or baseline in a future context where it is no longer relevant. Thus, to provide a meaningful comparison, this section contrasts the asphalt bank scenario in the current asphalt supply chain with that in the future.

Figure 8.8 compares the total supply chain costs and raw material usage in the asphalt supply chain for the current asphalt bank scenario (Case Study 1) and the future scenario with an asphalt bank (Case Study 2). Section 7.3.2, Case Study 2: The Future Asphalt Supply Chain With an Asphalt Bank, describes these configurations. This section further discusses several noteworthy points about the resulting simulations.

Figure 8.8: Comparing Supply Chain Cost and Raw Material Usage for the Current and Future Supply Chain With an Asphalt Bank.

Total Supply Chain Cost Comparison

The supply chain cost shows an overall increase in the future scenario compared to the current supply chain scenario. To be specific, the transport costs rise by €2,563,116, handling costs increase by €4,516,910, asphalt bank costs increase by €774,078, raw material costs grow by €5,282,485, and, finally, RAP processing costs rise by €3,190,216, a significant surge across all cost components. Resulting in a total supply chain cost increase for the future scenario compared to the current asphalt supply chain scenario of €16,326,804 over five years.

The total costs of the future supply chain are much higher but need some context. The future scenario involves a greater demand for asphalt and more RAP processing, which leads to bulkier material flows and, consequently, higher costs. When comparing the cost increase with the increase in asphalt production, it shows that while the asphalt production increases by 57.8% compared to the current scenario, the total cost only increases by 31.7%. Additionally, the average recycling percentage increases from 45.9% to 59.4%. That suggests that while more asphalt is produced and RAP material reused, the cost of asphalt production per ton has decreased as the total asphalt production increased by 57.8% and the total cost by only 31.7%.

Breakdown of Cost Components

The breakdown of individual cost components shows that transport costs increased by 58.9% and handling costs by 53.4%, which aligns with expectations. The transport cost increase closely matches the increase in asphalt production, with minor variations due to the different asphalt bank locations in the future scenario compared to the asphalt bank in the current asphalt supply chain scenario. The handling costs rise slightly less than the asphalt production, which can be attributed to the higher reuse of existing RAP, reducing the need for raw material purchases and associated loading and unloading (handling) practices.

Other costs increase relatively modestly, except the RAP processing costs. The asphalt bank costs rise by 11.1% due to a larger bank and a different location. Raw material costs increased by only 19.4%, despite a 57.8% increase in asphalt production due to the significant increase in the reuse of RAP. On the other hand, RAP processing costs increased significantly by 72.0%, reflecting the rise in asphalt production and recycling.

Raw Material Usage and Recycling Efficiency

The cost analysis suggests that increasing the asphalt demand makes the asphalts supply chain with an asphalt bank more cost-efficient. However, this is only partly true, as the applied recycling percentage also plays a crucial role. The more definitive conclusion is that a higher recycling percentage leads to increased throughput, thereby reducing the required storage capacity of an asphalt bank and, thus, the land-use costs. But at the same time, without any asphalt demand, no matter how high the recycling rate, there is no throughput at the asphalt bank. Section 8.4, Sensitivity Analysis of the Asphalt Supply Chain With an Asphalt Bank, further highlights the influence of the asphalt demand and recycling rates.

Nevertheless, despite pre-processing RAP being a cheaper resource than raw material, the future supply chain is similar to the current asphalt supply chain with an asphalt bank as it has lower recycling rates than the maximum allowed limits. While 65% of recycling is permitted in the asphalt surface layer and 70% in the binder and base layers, the actual recycling rates applied are 57.7% for the surface layer, 58.1% for the binder layer, and 61.1% for the base layer. The exact reason for not maximising the reuse of RAP is unclear. However, the optimisation model finds the situation with these reuse percentages cost-wise most optimal.

The following subsections provide additional information regarding the spatial and temporal dynamics of RAP and the storage of RAP in the asphalt banks, plus several noteworthy observations regarding asphalt production.

8.2.1 Spatial and Temporal Dynamics of RAP and Its Storage

This section examines the storage of Reclaimed Asphalt Pavement (RAP) across two asphalt banks, comparing their locations, storage capacities, and how RAP storage changes over time. Figure 8.10 and Figure 8.11 illustrate the asphalt banks in the current and future supply chain scenario, respectively.

A key observation from the simulations is that different asphalt banks were selected for the current and future supply chain scenarios, leading to distinct bank locations as shown in Figure 8.9. In the current scenario, the model selects Asphalt Bank 67, located in the De Hemmes industrial area in Zaandam. In contrast, Asphalt Bank 76, located in the "Noord" industrial area of Hoofddorp, was selected for the future scenario. These two banks are situated in opposite directions relative to Amsterdam, with a distance of over 19 kilometres between them. The reason for selecting a different location for the future scenario is most likely due to the amount of RAP released. Due to the release of more binder and base layers in the future scenario in particular maintenance locations and, thus, the increased amount of transport for these asphalt layers, it is probably logical to change the location of the asphalt bank.

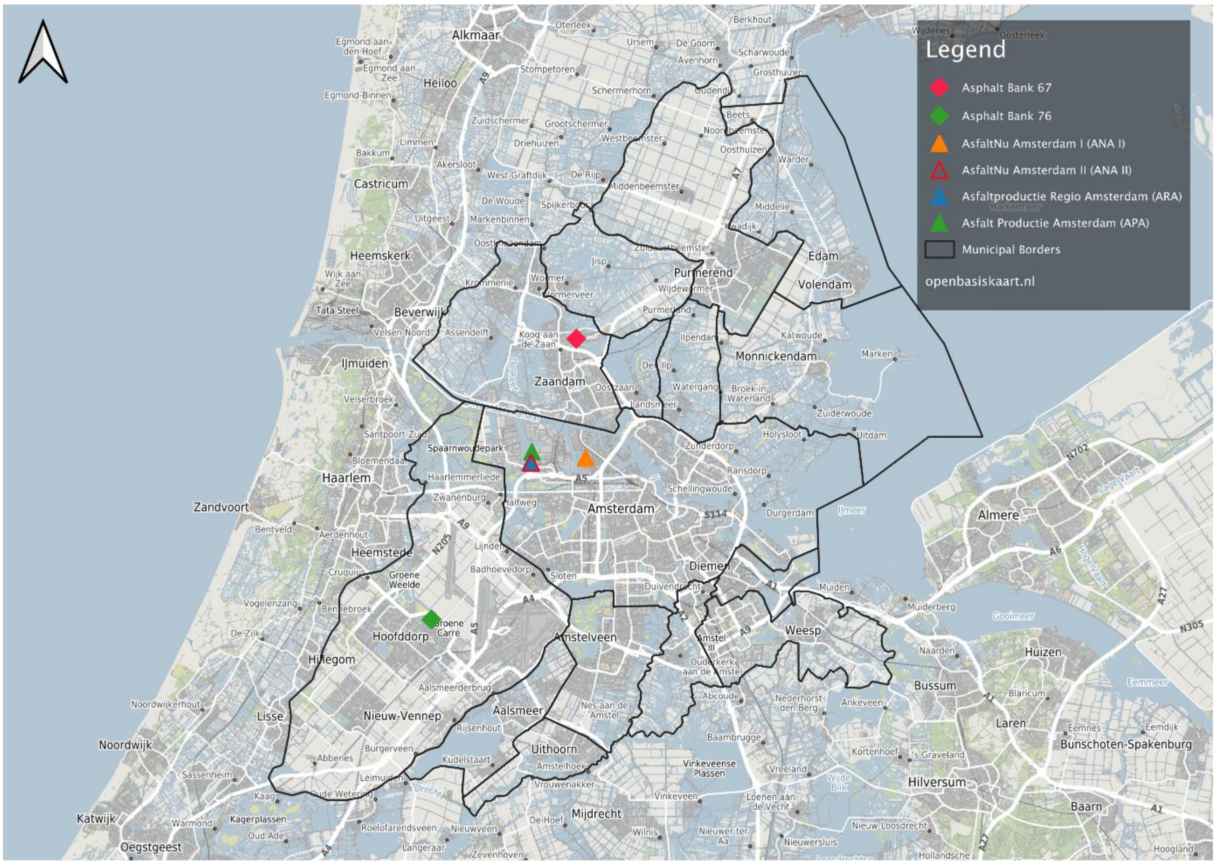

Figure 8.9: Location Candidate Asphalt Bank (67) and (76) in the Current and Future Supply Chain.

Despite the different locations, an analysis of RAP storage levels over time (as shown in Figure 8.10 and Figure 8.11) reveals minimal differences between the two scenarios. Although there are some variations, the overall storage trends are remarkably similar. Both scenarios show a relatively flat storage level until around month 40, followed by a gradual decrease and then a rapid increase to maximum storage capacity around month 50.

Looking closer at the storage capacities, Asphalt Bank 67, in the current scenario, has a maximum capacity of 164,181 m³. Asphalt Bank 76, in the future scenario, has a slightly larger capacity of 170,373 m³, representing a 3.8% increase in storage capacity compared to the current scenario. That is in contrast to a 57.8% increase in asphalt production, which implies a similar rise in RAP availability. This comparison reaffirms the earlier conclusion: higher recycling percentages and increased RAP throughput make asphalt banks more cost-efficient. In other words, in scenarios with a high demand for asphalt containing a high percentage of recycled material, a relatively smaller and, thus, less expensive asphalt bank is sufficient.

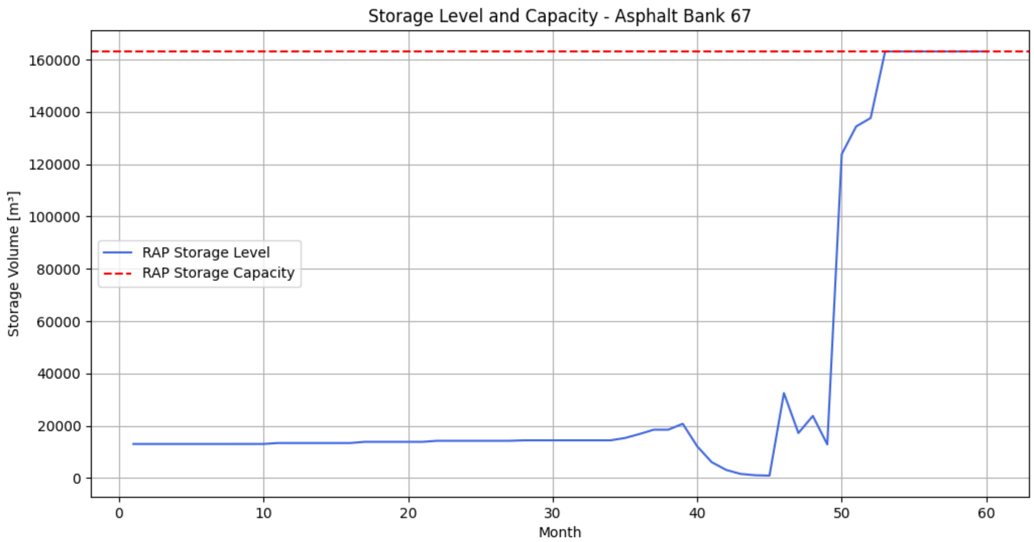

Figure 8.10: Storage Level and Capacity Asphalt Bank (67) in the Current Asphalt Supply Chain – Case Study 2.

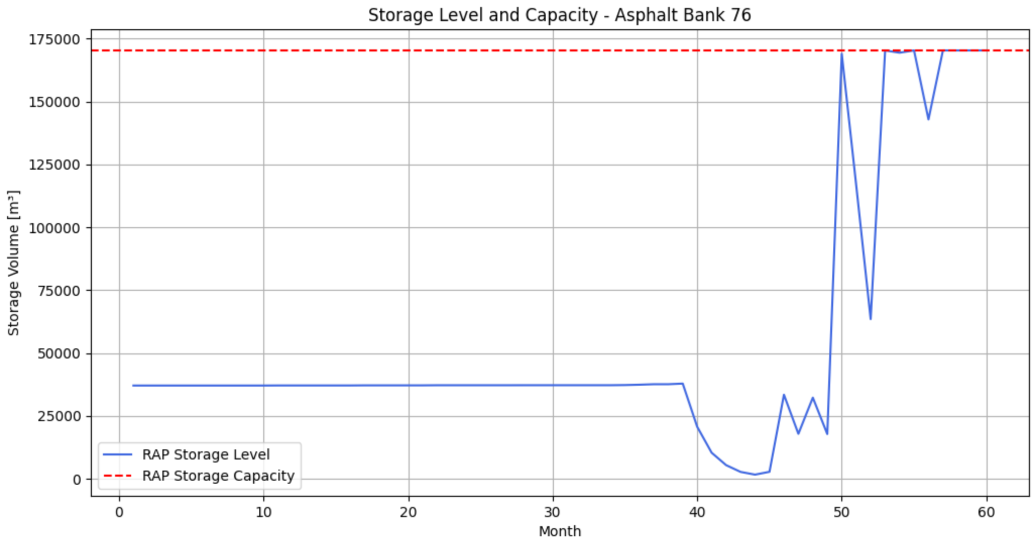

Figure 8.11: Storage Level and Capacity Asphalt Bank (76) in the Current Asphalt Supply Chain – Case Study 2.

The storage of RAP and raw materials at the four asphalt plants is similar to the situation described in Case Study 1 (see Figure 8.12). The raw material storage level starts at 60%. The raw material is consumed for asphalt production over the simulated time, causing the storage levels to decline, eventually reaching zero. The storage of RAP is not unusual or does not have unexpected aspects. In the future scenario, the total amount of RAP stored at the four asphalt plants might be slightly higher due to the increased availability of RAP. However, this increase is insignificant, as higher recycling rates compensate for the additional RAP. In summary, there are no surprises or unusual observations related to the storage process at the asphalt plants.

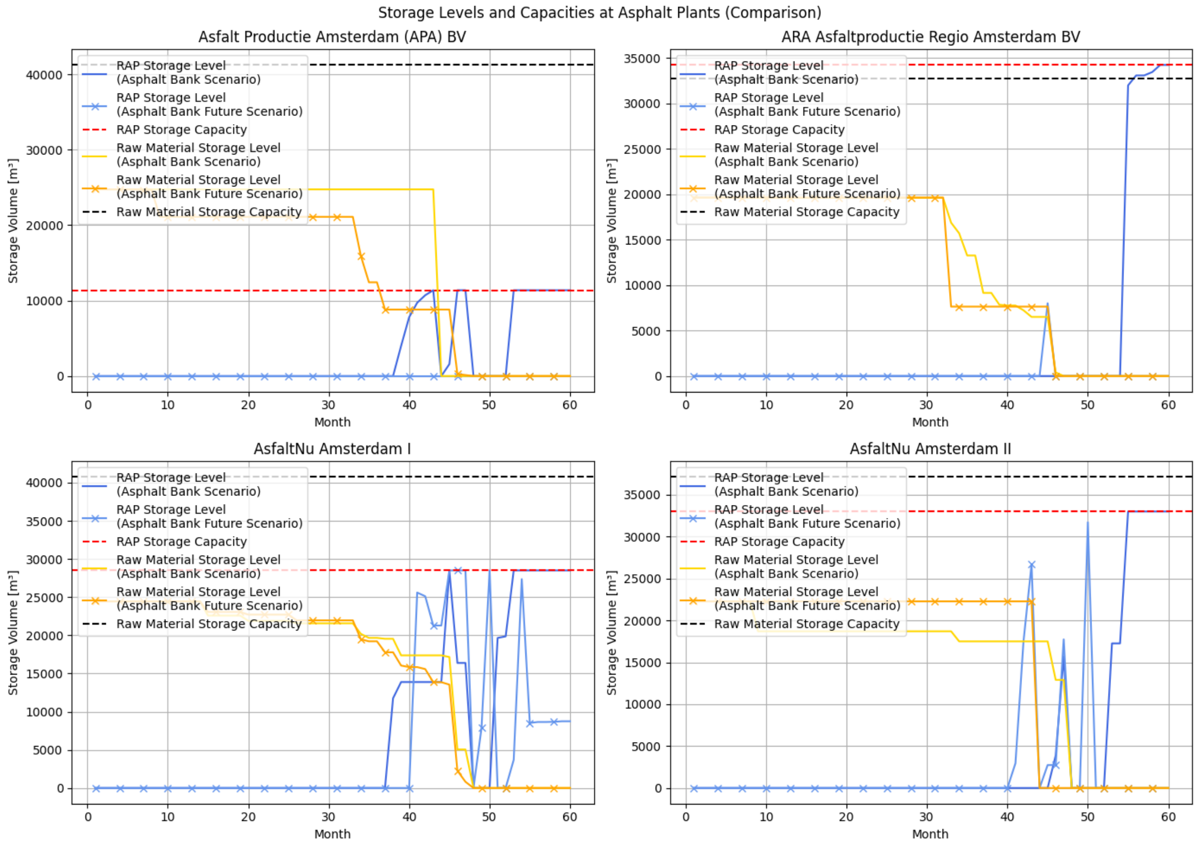

Figure 8.12: Comparison of Storage Levels and Capacities Asphalt Plants for the Current and Future Supply Chain With an Asphalt Bank.

8.2.2 Increased Asphalt Production

An in-depth analysis of the asphalt production data reveals some intriguing developments, particularly when comparing the following two asphalt plants: AsfaltNu Amsterdam I (ANA I) and AsfaltNu Amsterdam II (ANA II). ANA I stands out significantly from the other three asphalt plants in the future supply chain scenario. Meanwhile, the situation at ANA II is representative of the other two asphalt plants: ARA Asfaltproductie Regio Amsterdam BV and Asfalt Productie Amsterdam (APA) BV.

The asphalt production data for ANA I, as depicted in Figure 8.13, shows some particularly noteworthy differences between the current and future asphalt supply chain scenarios. In the future, asphalt recycling, specifically in the asphalt top layer, and asphalt demand significantly increase. However, initially unexpected, the total asphalt production for ANA I decreases in the future scenario. That makes ANA I unique compared to the other asphalt plants, where asphalt production generally increases significantly.

When examining the asphalt production per asphalt layer, we see a decrease in the production of the asphalt top and binder layers, with only a slight increase in the asphalt base layer. Interestingly, this increase in the base layer is relatively modest compared to the fivefold increase in demand for asphalt in the base layer in the future scenario. The reason for the reduced asphalt production at asphalt plant ANA I in the future scenario, compared to the current one, is the asphalt bank location and its impact on the RAP material flows. In the future scenario, asphalt plant ANA I lies furthest from the asphalt bank, and to minimise the transport of RAP material and the associated transport costs, the model reduces the asphalt production at this plant.

Further analysis of the inflows of RAP material and raw material in the future scenario highlights the characteristics of the future asphalt supply chain scenario. Despite the overall decrease in asphalt production, there are two notable trends: the inflow of RAP material decreases but not significantly, while the inflow of raw materials decreases very significantly. The overall decrease in inflows is due to the reduced asphalt production. The sharp decline in raw material inflows compared to a slight reduction in RAP inflows is due to the increased recycling rates. With more recycling, less raw material is needed in asphalt production, which means to produce the same amount of asphalt, more RAP material is required, leading to a less significant decrease in RAP inflow despite the reduction in asphalt production. In summary, ANA I uniquely illustrates several aspects of the future asphalt supply chain scenario.

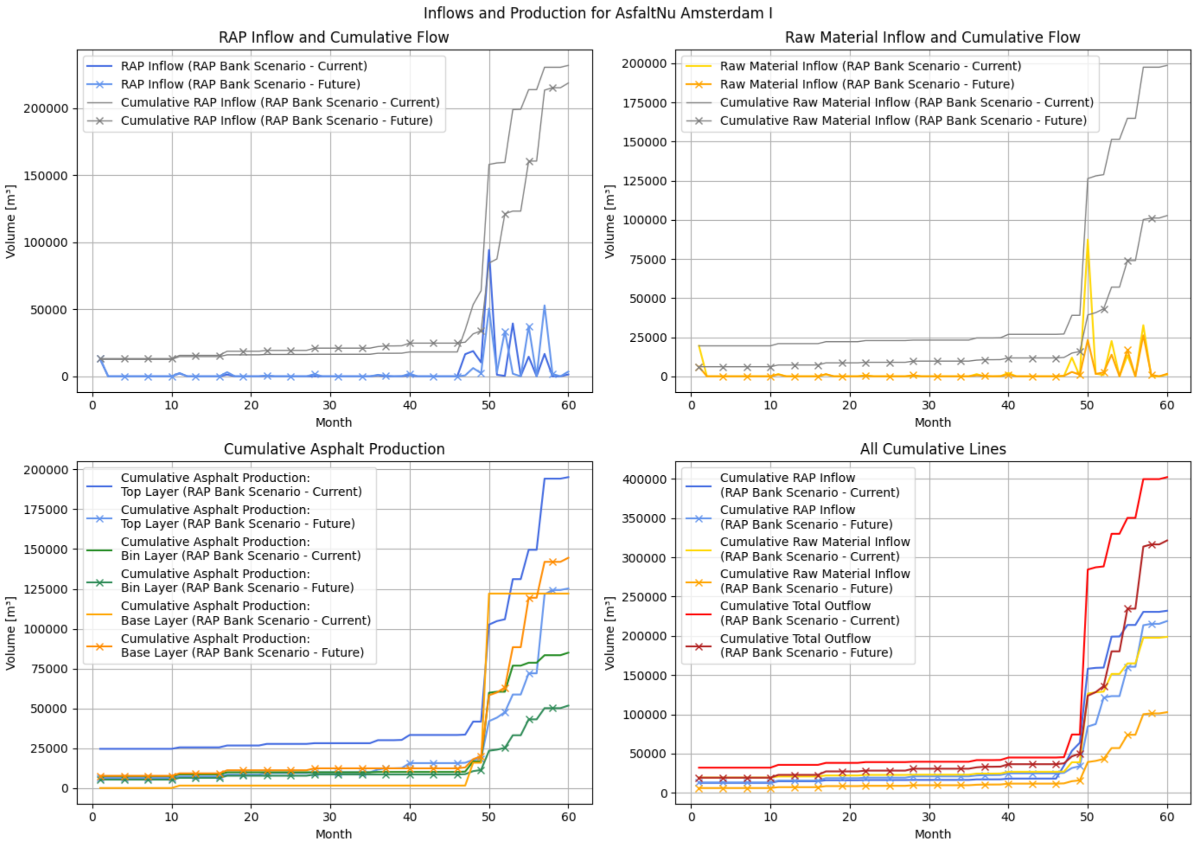

Figure 8.13: Comparison of Asphalt Production ANA I for the Current and Future Supply Chain With an Asphalt Bank.

The production data for ANA II, shown in Figure 8.14, aligns more closely with the expectations before the simulation. This data also mirrors the data of ARA Asfaltproductie Regio Amsterdam BV and Asfalt Productie Amsterdam (APA) BV. In the future scenario, ANA II experiences a significant increase in asphalt production, particularly in the base layer, which increases nearly fivefold. The production of the top and binder layers also rises, with the increase in the top layer likely due to the decrease in production at ANA I.

The inflow of RAP and raw materials at ANA II and the other two plants also increase significantly reflecting the higher asphalt production. Notably, the intake of RAP increases more significantly than that of raw materials, which is consistent with the higher allowable percentage of recycled material in the asphalt surface layer in the future scenario.

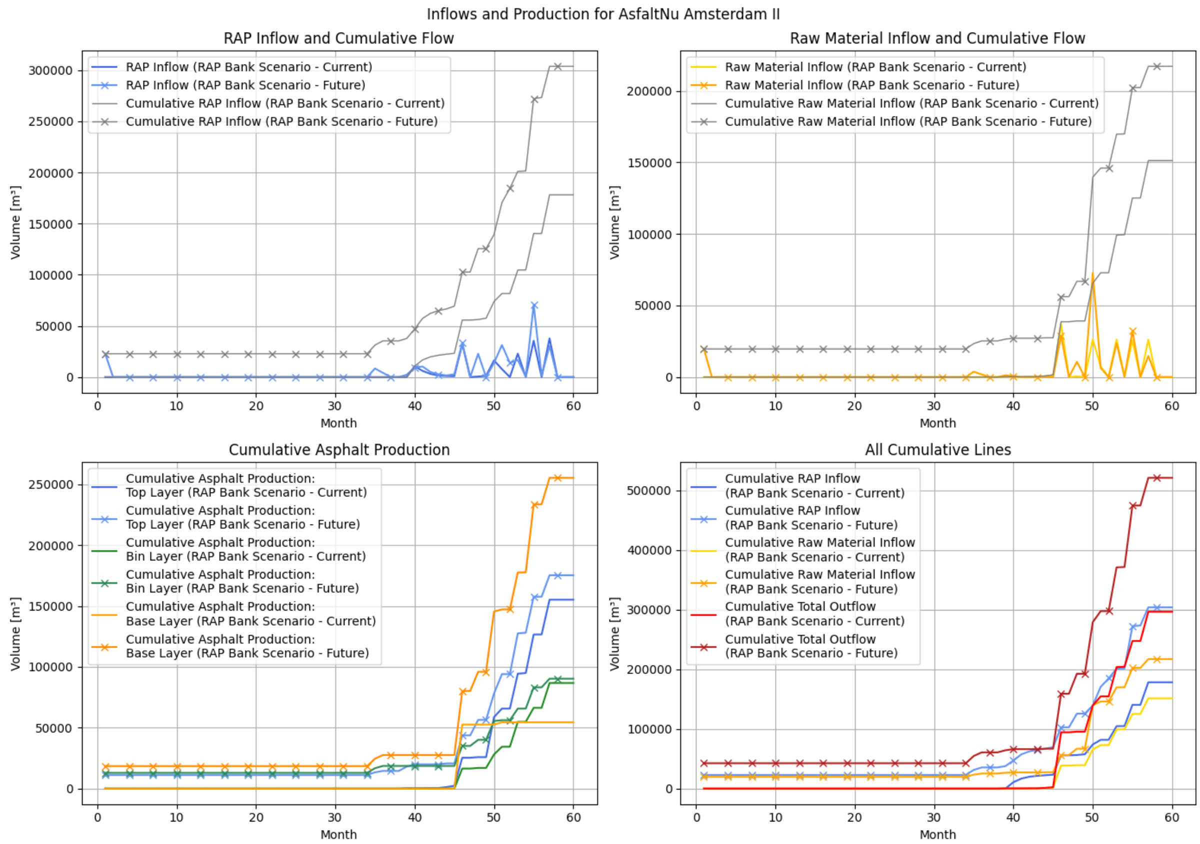

Figure 8.14: Comparison of Asphalt Production ANA II for the Current and Future Supply Chain With an Asphalt Bank.

Lastly, examining the overproduction or slack production data of the asphalt plants (Figure 8.15) confirms the previously discussed unique situation of AsfaltNu Amsterdam I (ANA I) in the future supply chain scenario. Generally, slack production increases due to rising asphalt demand. However, the situation at ANA I is again exceptional, with a decrease in overproduction in the future scenario. That contrasts with ANA II, ARA, and APA, where overproduction increases to meet the growing demand for asphalt.

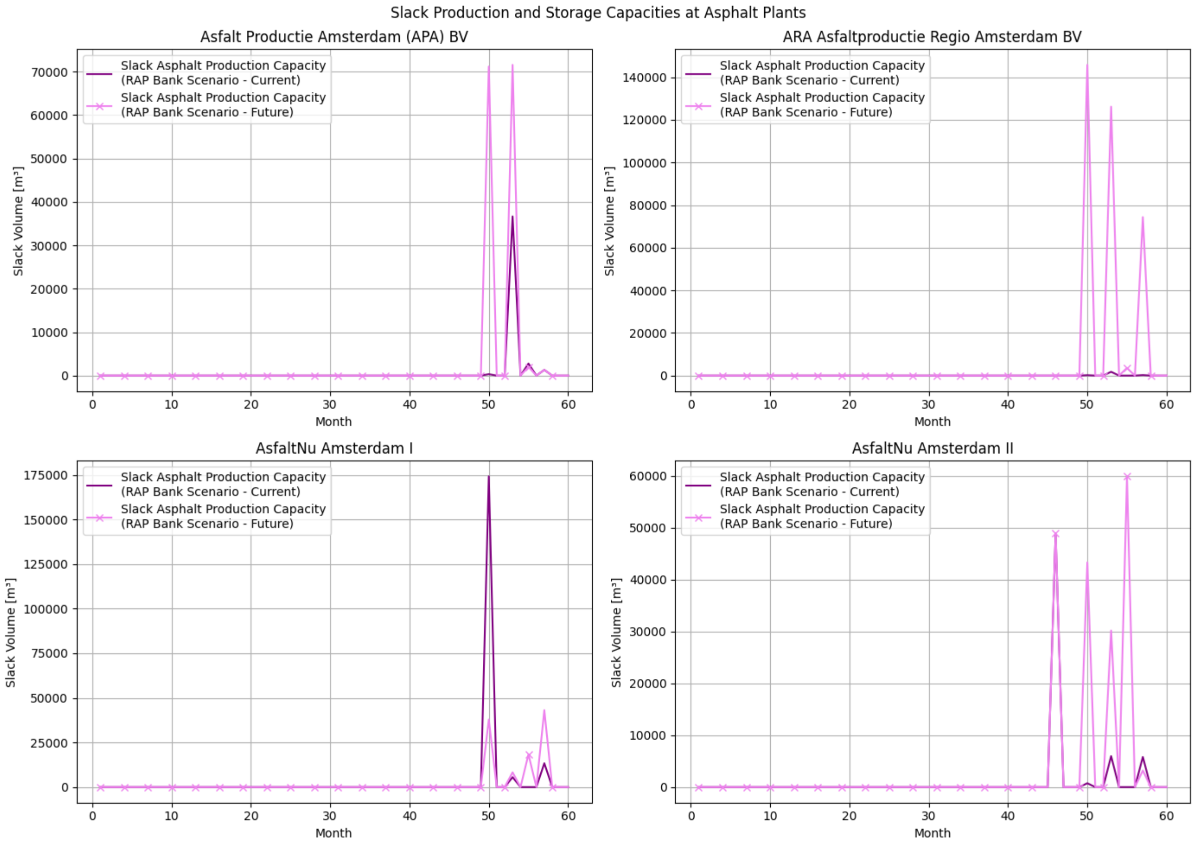

Figure 8.15: Comparison of Slack Asphalt Production for the Current and Future Supply Chain With an Asphalt Bank.

8.3 Case Study 3: The Current Asphalt Supply Chain With Multiple Asphalt Banks

The model of the two previous case study scenarios was limited to selecting only a single candidate asphalt bank location. The simulation of Case Study 3 represents the asphalt supply chain in which the number of asphalt banks is only limited by the available candidate asphalt bank locations. In this case, the model can optimise the number of asphalt banks. This subsection compares Case Study 1 with a single asphalt bank and Case Study 3 with an optimal number of asphalt banks. It examines the total supply chain costs, the number of asphalt banks, their location, and the effects on RAP's spatial and temporal distribution.

Figure 8.16 illustrates the total supply chain cost and raw material usage in the asphalt supply chain for the two scenarios: Case Study 1 with a single asphalt bank and Case Study 3 with an optimal number of asphalt banks, found to be four. The key observations from this comparison are discussed further in this subsection.

Figure 8.16: Comparing Supply Chain Cost and Raw Material Usage for the Single and Multiple Asphalt Bank Scenario Analysis.

Total Supply Chain Cost Analysis

The comparison (see Figure 8.16) reveals that using multiple asphalt banks offers an economic advantage, reducing the total supply chain costs by €649,132 over five years – a decrease of 1.3%. The primary cost components that vary between the single and multiple asphalt bank scenarios are the transport cost and asphalt bank cost components. While the combined variation in handling, raw material, and RAP processing costs is less than €5,000 – an insignificant difference – the costs associated with the asphalt banks themselves increase by €131,584, or 1.9%, due to the construction of four banks in the multiple-bank scenario. However, on the other hand, transport costs are substantially decreased by €787,008, representing an 18.1% reduction.

Although the total supply chain costs increase with the introduction of asphalt banks compared to the current scenario without any, primarily due to the costs associated with the banks, additional handing, and extra transport, the transport cost difference between the current supply chain and the scenario with asphalt banks narrows when using multiple banks. In comparison, the transport costs in the single-bank scenario are €1,110,988 higher than in the current supply chain, reflecting a 34.3% increase. However, with multiple asphalt banks, the difference in transport costs is reduced to just €323,979 over five years - only a 10% increase compared to the current supply chain. That indicates that optimising the number of asphalt banks in a region can significantly reduce transport costs, mitigating the overall cost increase compared to the existing supply chain.

The following subsection will delve into the spatial and temporal distribution of RAP, its storage, and the locations of the asphalt banks.

8.3.1 Asphalt Banks and Their Effect on the Spatial and Temporal Distribution of RAP

A detailed look at the asphalt banks shows how the model with fewer restrictions arrives at an optimal number of four asphalt banks within the Amsterdam Transport Region. Figure 8.17 shows the four asphalt bank locations for the supply chain scenario with multiple asphalt banks. Note that Asphalt Bank 67 is the single asphalt bank selected for the restricted supply chain scenario. Asphalt Banks 28, 67, 76, and 91 are the four asphalt banks for the nonrestricted supply chain scenario. The asphalt bank numbers represent the ID number for the asphalt bank location.

These asphalt banks are located on the following industrial terrains: Asphalt Bank 28 in the Westhaven area, an industrial terrain in Amsterdam, close to the four asphalt plants; Asphalt Bank 67 in the De Hemmes industrial area in Zaandam; Asphalt Bank 76 in the "Noord" industrial area of Hoofddorp; and Asphalt Bank 91 in an unnamed industrial terrain in the town of Edam in the Northern part of the Amsterdam Transport Region.

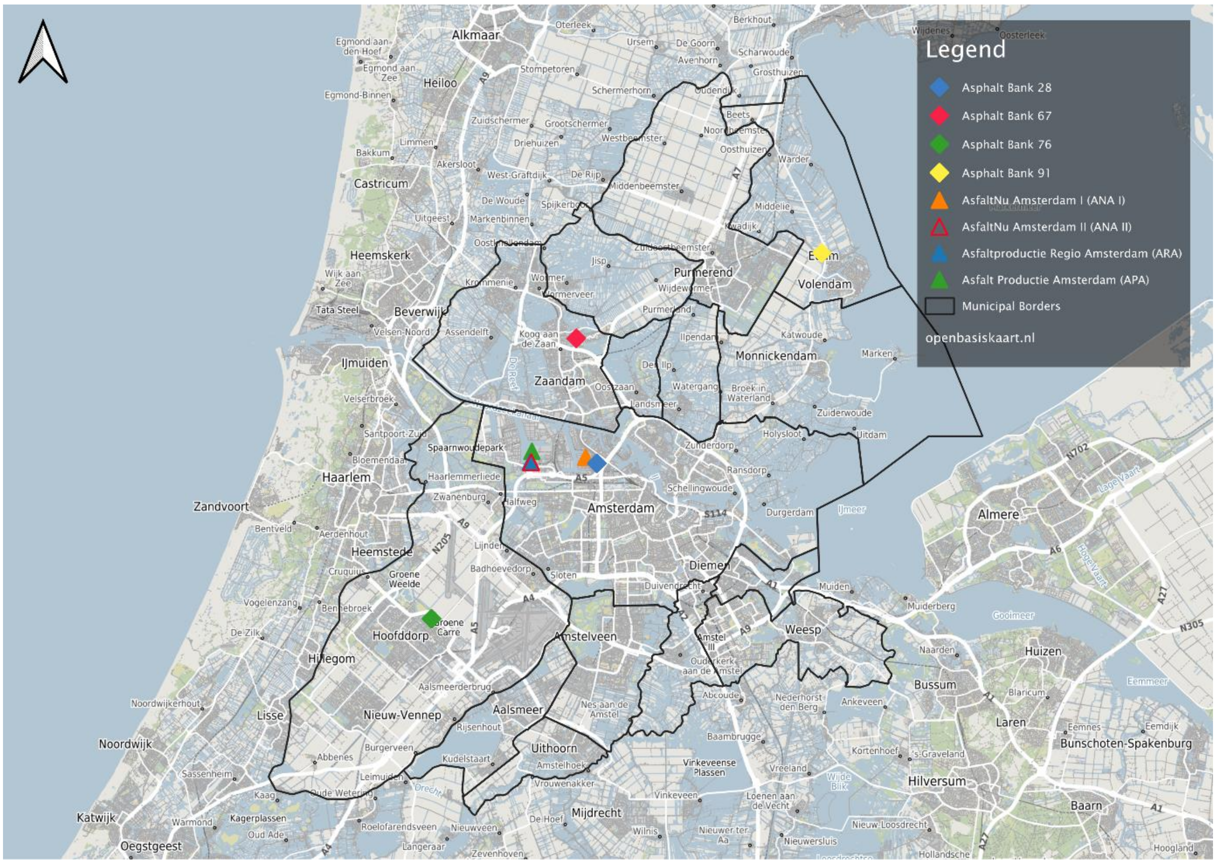

Figure 8.17: Location Candidate Asphalt Bank (28), (67), (76), and (91) for the Single and Multiple Asphalt Bank Scenario Analysis.

Besides the difference in the number of asphalt banks and thus their locations, they are different in size. In the scenario with a single asphalt bank, Asphalt bank 67, all RAP must be stored in that particular asphalt bank, which means that the asphalt bank must have such a capacity, a capacity of 164.181 m³ in this case. Figure 8.18 shows the course of RAP over time for asphalt bank 67 in the single asphalt bank scenario.

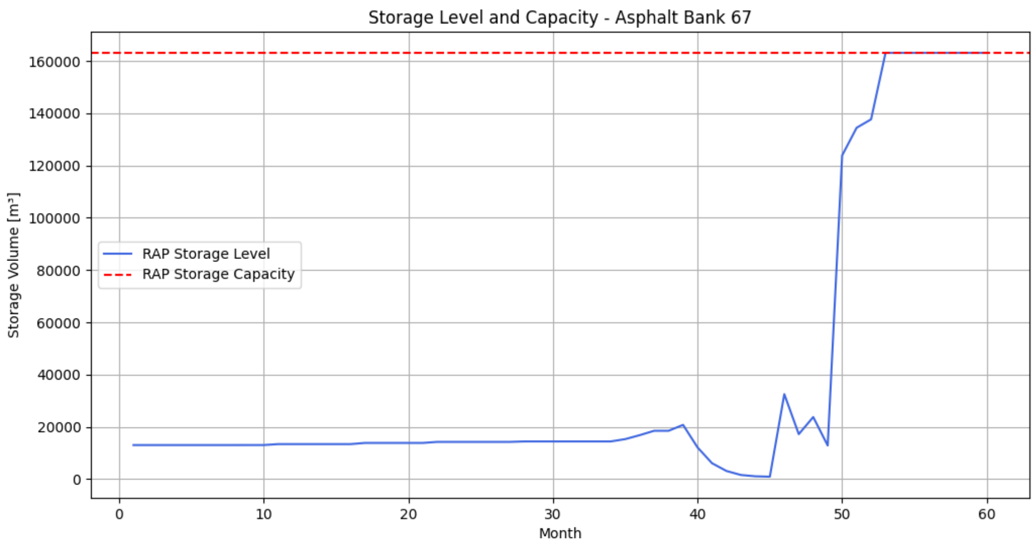

Figure 8.18: Storage Level and Capacity Asphalt Bank (67) for the Single Asphalt Bank Scenario.

In the case of the multiple asphalt bank scenario, there are four asphalt banks over which the required storage capacity for RAP can be divided. Because the other input parameters do not change in this scenario, the total storage capacity for RAP is almost the same for both scenarios. The combined storage capacity of the four asphalt banks is 163,824 m³, a decrease of 0.3% compared to the single asphalt bank scenario.

Figure 8.19 shows the storage capacity and the development of RAP storage level over time for Asphalt Bank 28, with a storage capacity of 32361 m³. Figure 8.20 shows the storage capacity and the development of RAP storage level over time for Asphalt Bank 67, with a storage capacity of 15322 m³. Figure 8.21 shows the storage capacity and the development of RAP storage level over time for Asphalt Bank 76, with a storage capacity of 43846 m³. Figure 8.22 shows the storage capacity and the development of RAP storage level over time for Asphalt Bank 91, with a storage capacity of 72295 m³.

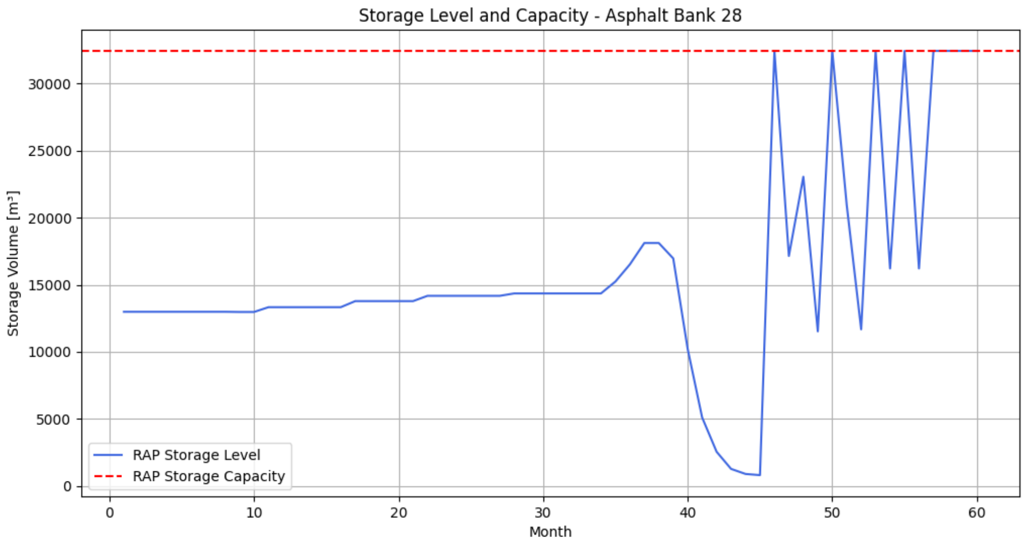

Figure 8.19: Storage Level and Capacity Asphalt Bank (28) for the Multiple Asphalt Bank Scenario.

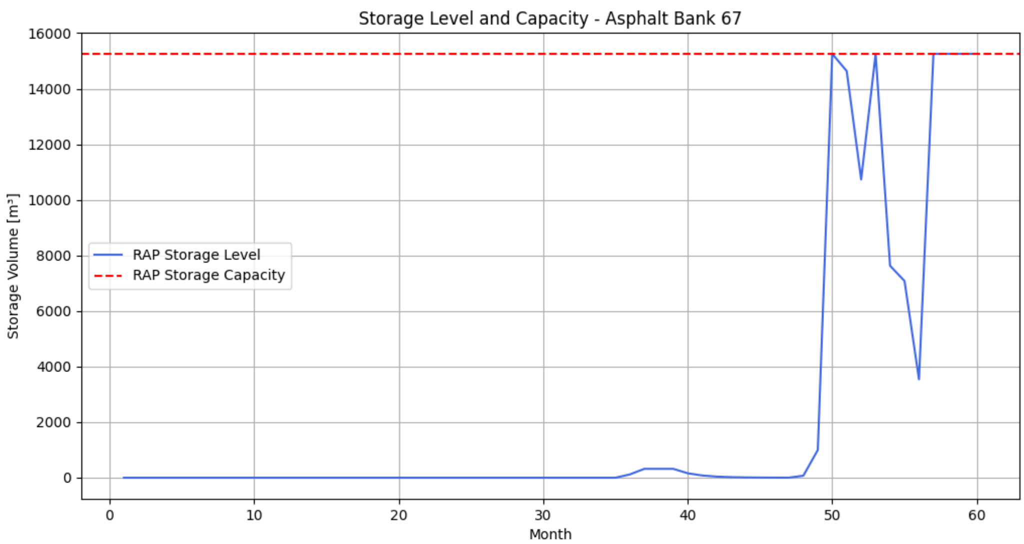

Figure 8.20: Storage Level and Capacity Asphalt Bank (67) for the Multiple Asphalt Bank Scenario.

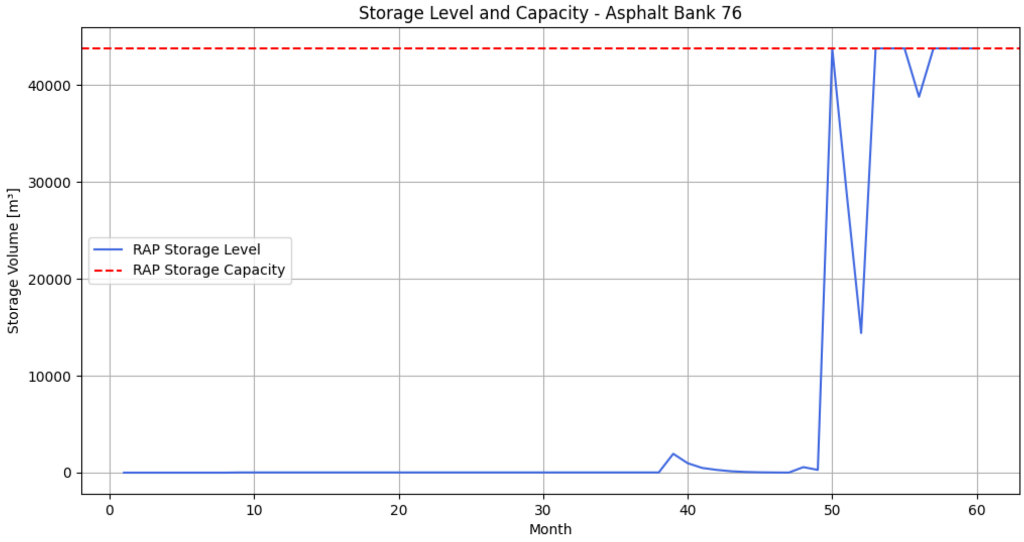

Figure 8.21: Storage Level and Capacity Asphalt Bank (76) for the Multiple Asphalt Bank Scenario.

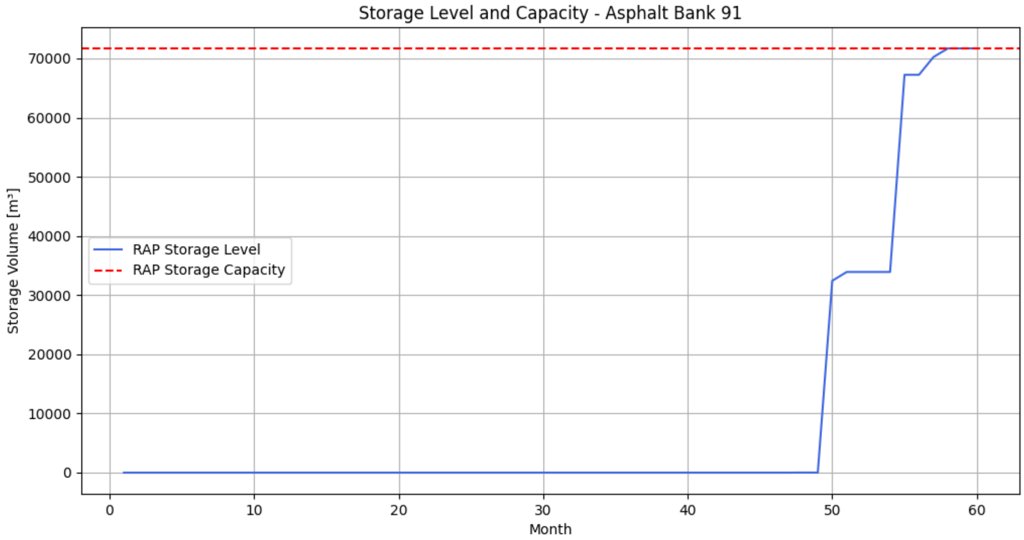

Figure 8.22: Storage Level and Capacity Asphalt Bank (91) for the Multiple Asphalt Bank Scenario.

Looking at the progression of RAP storage levels over time at the four asphalt banks, something stands out. The three asphalt banks located close to the four asphalt plants, Asphalt Bank 28, 67, and 76, consistently supply RAP to the asphalt plants, as can be seen from the decreases in their RAP storage levels over time. In contrast, Asphalt Bank 91 supplies little RAP to the asphalt plants and is a larger storage facility at a more remote, lower-cost location where RAP material is stored for an extended time.

In summary, multiple asphalt banks are cheaper than a single asphalt bank. In addition, there are other advantages to multiple asphalt banks in terms of the system's flexibility and the possibility to optimise particular banks, for example, for processing RAP and short-term storage or long-term RAP storage. On the other hand, there are disadvantages to multiple asphalt banks, such as the system's complexity and the management of numerous asphalt bank locations, especially if one considers different RAP types and fractions.

8.4 Sensitivity Analysis of the Asphalt Supply Chain With an Asphalt Bank

In addition to the three case studies, two sensitivity analyses gain further insights into the model's robustness and explore how specific parameters or scenarios affect the model, the asphalt bank, and RAP's spatial and temporal dynamics. These sensitivity analyses focus on two critical aspects: (1) RAP inflow and asphalt demand and (2) asphalt recycling rates.

The following two subsections present, explain and interpret the results of these sensitivity analyses. A detailed discussion of the outcomes of these analyses can be found in Chapter 9, Discussion.

8.4.1 RAP Availability and Asphalt Demand

This section presents the sensitivity analysis of RAP availability and asphalt demand, examining their effects on supply chain costs, asphalt banks, and RAP's spatial and temporal dynamics. Four model simulations were performed with varying RAP supply and asphalt demand rates. Notably, while the simulation with 80% RAP supply and 20% asphalt demand identified an optimal solution, it did not yield usable results. Consequently, the comparison focuses on the two extreme scenarios that produced results, as the intermediate case aligns with expected patterns and does not contribute significantly to the analysis.

Nevertheless, it is worth mentioning that the design of this sensitivity analysis is flawed because, while it allows for comparison between scenarios, it does not enable well-founded conclusions about the impact of the specific parameters, like the effects of varying RAP supply or asphalt demand independently. In these scenarios, RAP supply and asphalt demand change simultaneously, making it difficult to isolate the influence of individual parameters. Despite these limitations, the scenarios have been compared, and observations are briefly discussed.

Figure 8.23 illustrates the total supply chain cost and raw material usage in the asphalt supply chain for two scenarios: 20% RAP supply with 80% asphalt demand (S&D 20 - 80) and 60% RAP supply with 40% asphalt demand (S&D 60 - 40). The key observations from this comparison are discussed further in this subsection.

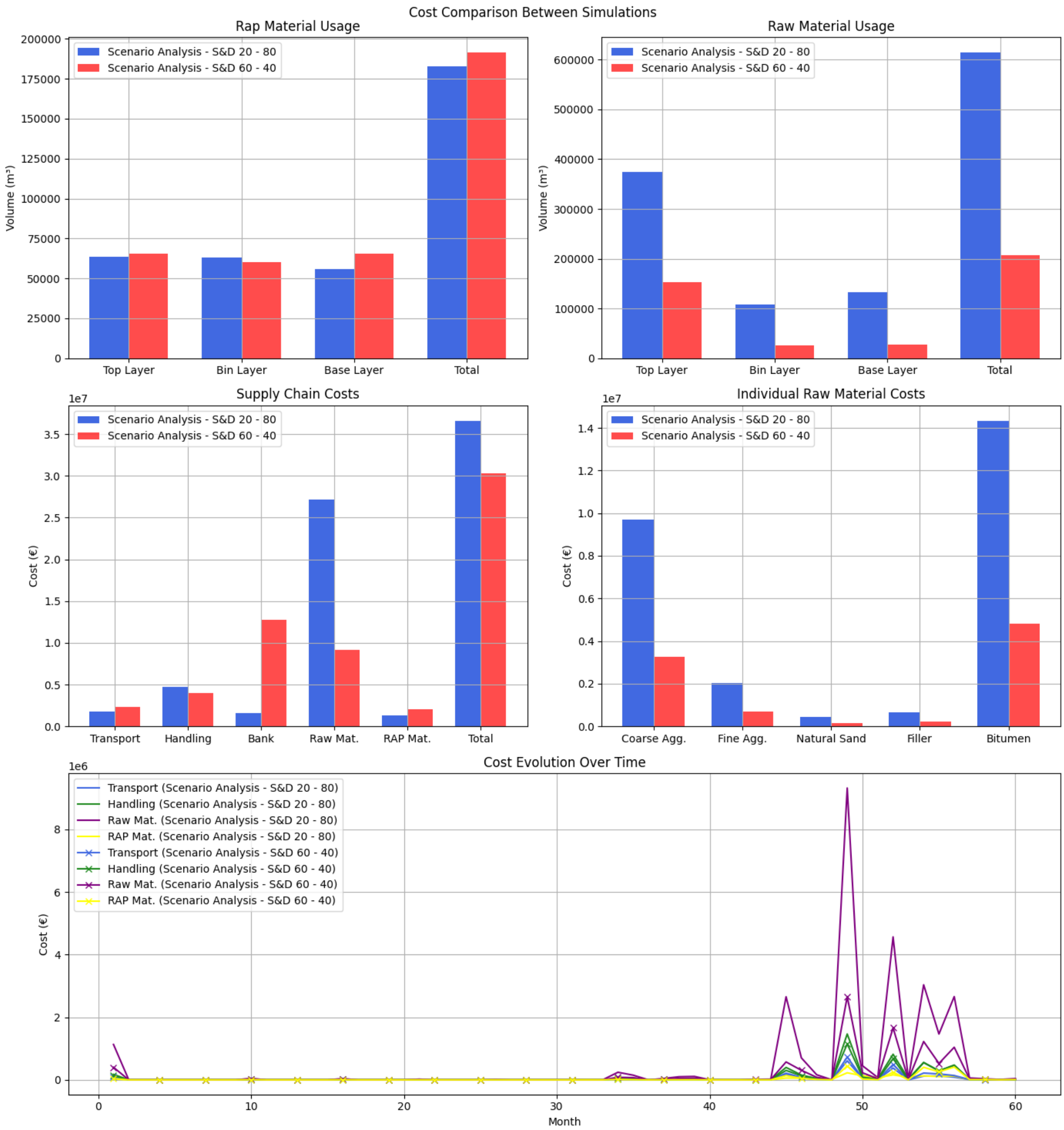

Figure 8.23: Comparing Supply Chain Cost and Raw Material Usage for the 20% Supply 80% Demand and 60% Supply 40% Demand Scenario Analysis.

Total Supply Chain Cost Analysis

The comparison (see Figure 8.23) compares relatively low inflow and high demand vs. high inflow and low demand at the asphalt bank and asphalt supply chain generally. The following observations are drawn from this comparison.

In the low supply and high demand scenario (S&D 20 – 80), raw material costs are significantly higher than in the high supply and low demand scenario (S&D 60 – 40). That is because a higher demand for asphalt, coupled with a low RAP supply, necessitates the production of asphalt using mostly new raw materials. Conversely, in the S&D 60 – 40 scenario, the abundant RAP supply allows for extensive use of RAP in asphalt production, reducing the need for new raw materials.

The opposite trend can be observed in RAP processing costs. In the S&D 20 - 80 scenario, where the RAP available is low, less RAP gets pre-processed, leading to lower processing costs. In the S&D 60 - 40 scenario, the abundant RAP supply results in higher processing costs despite the lower asphalt demand as more RAP gets used in asphalt production.

Consequently, due to the low RAP supply, the asphalt bank is smaller in the S&D 20 - 80 scenario due to the limited supply of RAP, leading to significantly lower storage costs. The handling costs are higher in this scenario, indicating more material gets circulated within the supply chain. However, transport costs are lower in the S&D 20 - 80 scenario when compared to the S&D 60 - 40 scenario. That is because, in the S&D 60 - 40 scenario, more RAP must be transported from the road to the asphalt bank, a longer distance when compared to transporting raw materials directly from the raw material supply to the asphalt plants as in the S&D 20 - 80 scenario.

Raw Material Usage

As noted in the introduction, comparing the results between these two scenarios is challenging, especially for material usage, due to the simultaneous difference in RAP availability and asphalt demand. Nevertheless, the scenarios are briefly examined individually. Before discussing the scenarios, it is good to indicate that in both scenarios, 30% recycling in the asphalt top layer and 70% recycling in the binder and base layer were permitted.

In the low supply and high demand scenario (S&D 20 - 80), limited RAP is available for reuse, leading to only 25.4% recycling in the top layer, 47.1% in the binder layer, and 37.9% in the base layer. Interestingly, RAP material remains available at the asphalt bank (Figure 8.25), while storage at asphalt plants is empty. That suggests that in this particular situation, it is economically more advantageous to use raw materials instead of maximising RAP reuse.

In the high supply and low demand scenario (S&D 60 - 40), the abundant RAP supply allows maximum recycling - 30% in the surface layer and 70% in the binder and base layers. Asphalt plants maximise their RAP storage to alleviate the storage burden on the asphalt bank (Figure 8.26). Although this scenario is theoretically possible, it is unlikely to occur in practice where there is an excessive amount of RAP supply relative to the demand for asphalt.

The following subsection will delve into the spatial and temporal distribution of RAP, its storage, and the locations of the asphalt banks.

8.4.1.1 The Effect of RAP Supply and Asphalt Demand on the Asphalt Bank Locations

An analysis of the asphalt banks reveals that the amount of RAP to be stored influences the capacity of the asphalt banks and, thereby, the location of the asphalt bank. Figure 8.24 highlights the locations of asphalt banks for two scenarios: low RAP supply and high asphalt demand (S&D 20 - 80) and high RAP supply and low asphalt demand (S&D 60 - 40). In the S&D 20 - 80 scenario, Asphalt Bank 28 is selected, while in the S&D 60 - 40 scenario, Asphalt Bank 67 is chosen.

These asphalt banks are in different industrial areas: Asphalt Bank 28 is in the Westhaven area of Amsterdam, close to the four asphalt plants, whereas Asphalt Bank 67 is in the De Hemmes industrial area of Zaandam.

A notable difference between the two scenarios (apart from their location) is the significant disparity in the size of the asphalt banks (see Figure 8.25 and Figure 8.26). This difference is expected, given that the S&D 60 - 40 scenario has three times the RAP supply and only half the asphalt demand compared to the S&D 20 - 80 scenario.

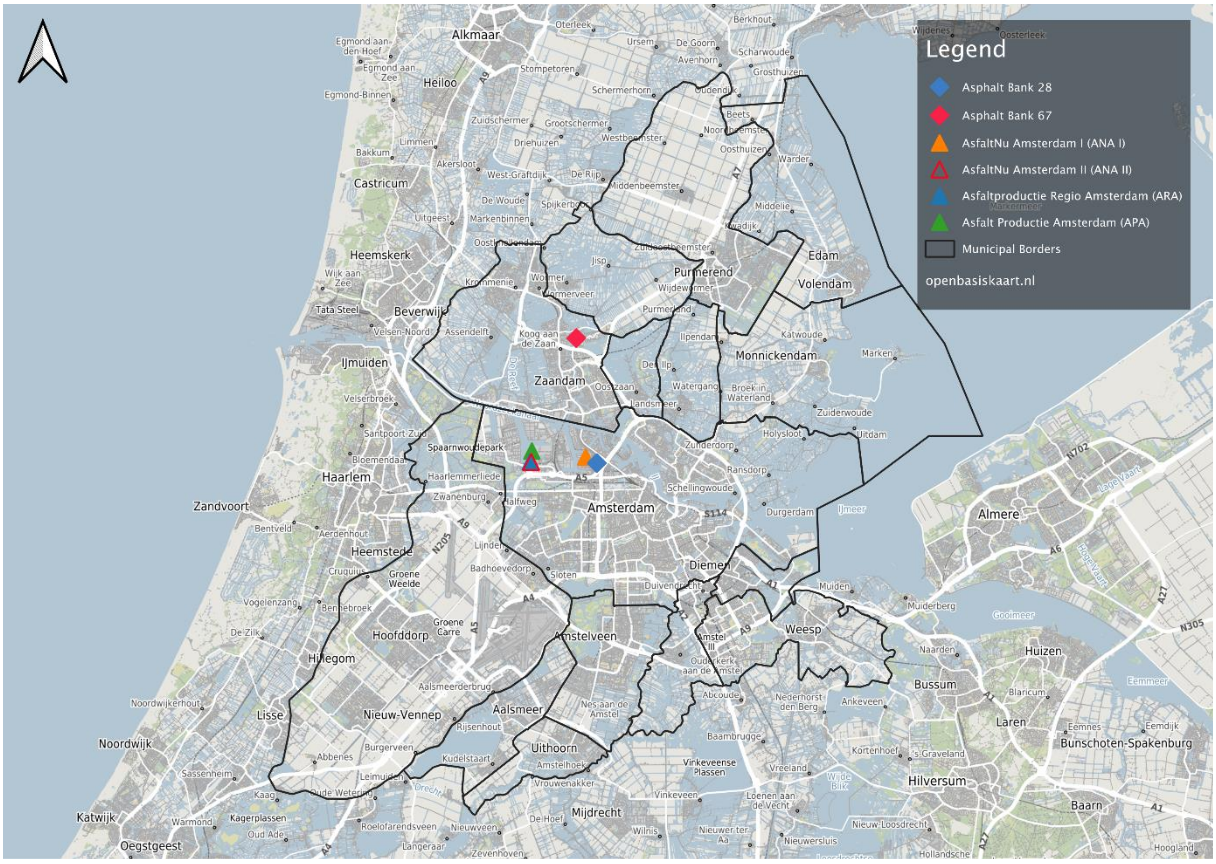

Figure 8.24: Location Candidate Asphalt Bank (28) and (67) for the 20% Supply 80% Demand and 60% Supply 40% Demand Scenario Analysis.

In the S&D 20 - 80 scenario, the limited RAP supply and higher asphalt demand require a relatively small storage capacity. Figure 8.25 shows the RAP storage levels and capacity of Asphalt Bank 28, which has a capacity of only 30,973 m³ due to the small amount of RAP available and the high demand for asphalt.

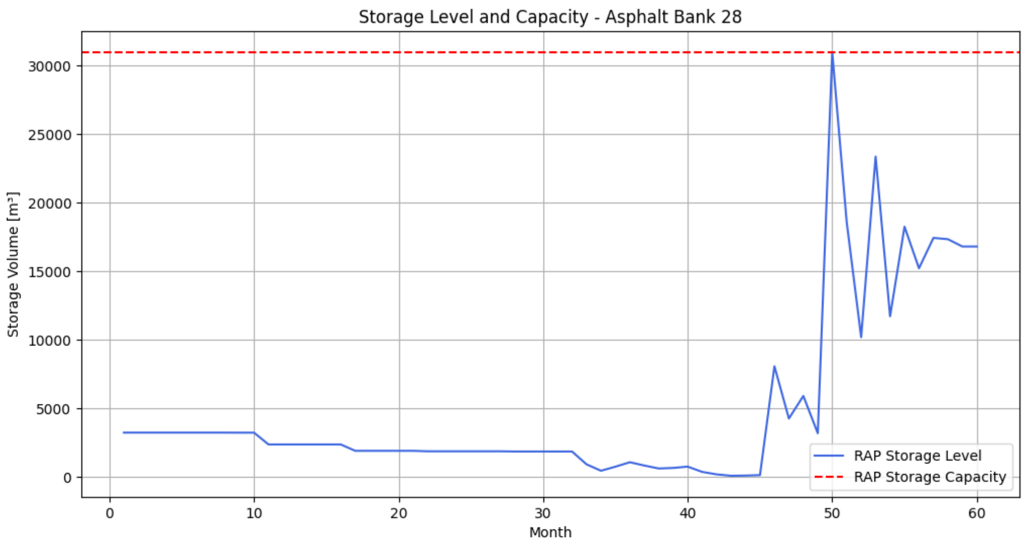

Figure 8.25: Storage Level and Capacity Asphalt Bank (28) for the 20% supply and 80% Demand Scenario Analysis.

Conversely, in the S&D 60 – 40 scenario, the abundant RAP supply and lower asphalt demand necessitate a much larger storage capacity. Figure 8.26 illustrates the RAP storage levels and capacity of Asphalt Bank 67, which is significantly larger than Asphalt Bank 28, with a capacity of 298,054 m^3.

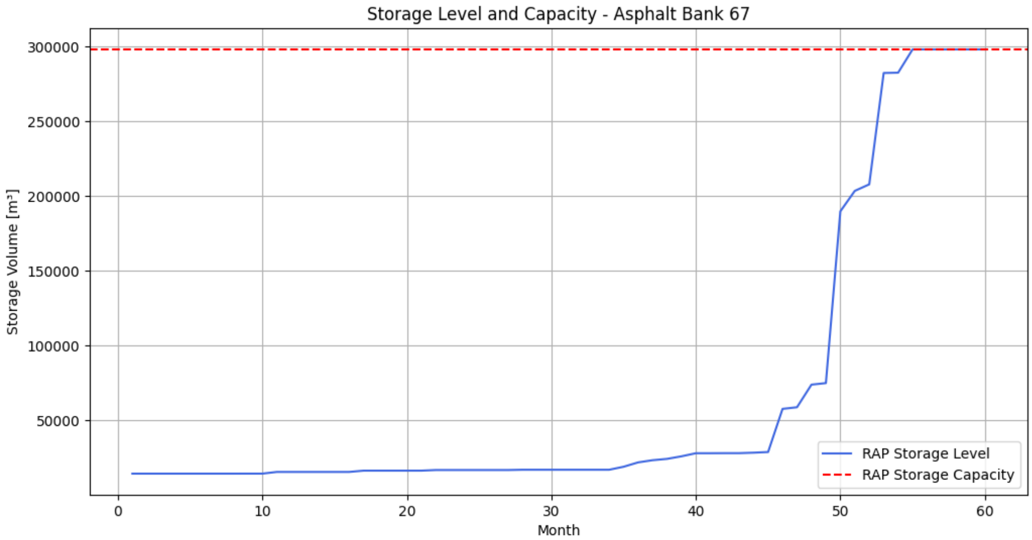

Figure 8.26: Storage Level and Capacity Asphalt Bank (67) for the 60% Supply 40% Demand Scenario Analysis.

Comparing the two scenarios suggests that as the size of an asphalt bank decreases, it becomes economically advantageous to relocate from the less expensive Asphalt Bank 67 to the more costly Asphalt Bank 28. This shift reduces transport costs, making it more cost-effective to position the asphalt bank closer to the asphalt plants.

8.4.2 Asphalt Recycling Rates

The final scenario analysis focuses on the permitted asphalt percentages. In this analysis, four model simulations were performed with varying recycling rates. However, for comparison, the focus is on the two extreme scenarios, as the intermediate cases align with expected patterns and do not significantly contribute to the analysis.

Figure 8.27 illustrates the total supply chain cost and raw material usage in the asphalt supply chain for the minimal (RR 30-50-50) and maximal (RR 65-90-90) recycling scenarios. The key observations from this comparison are discussed further in this subsection.

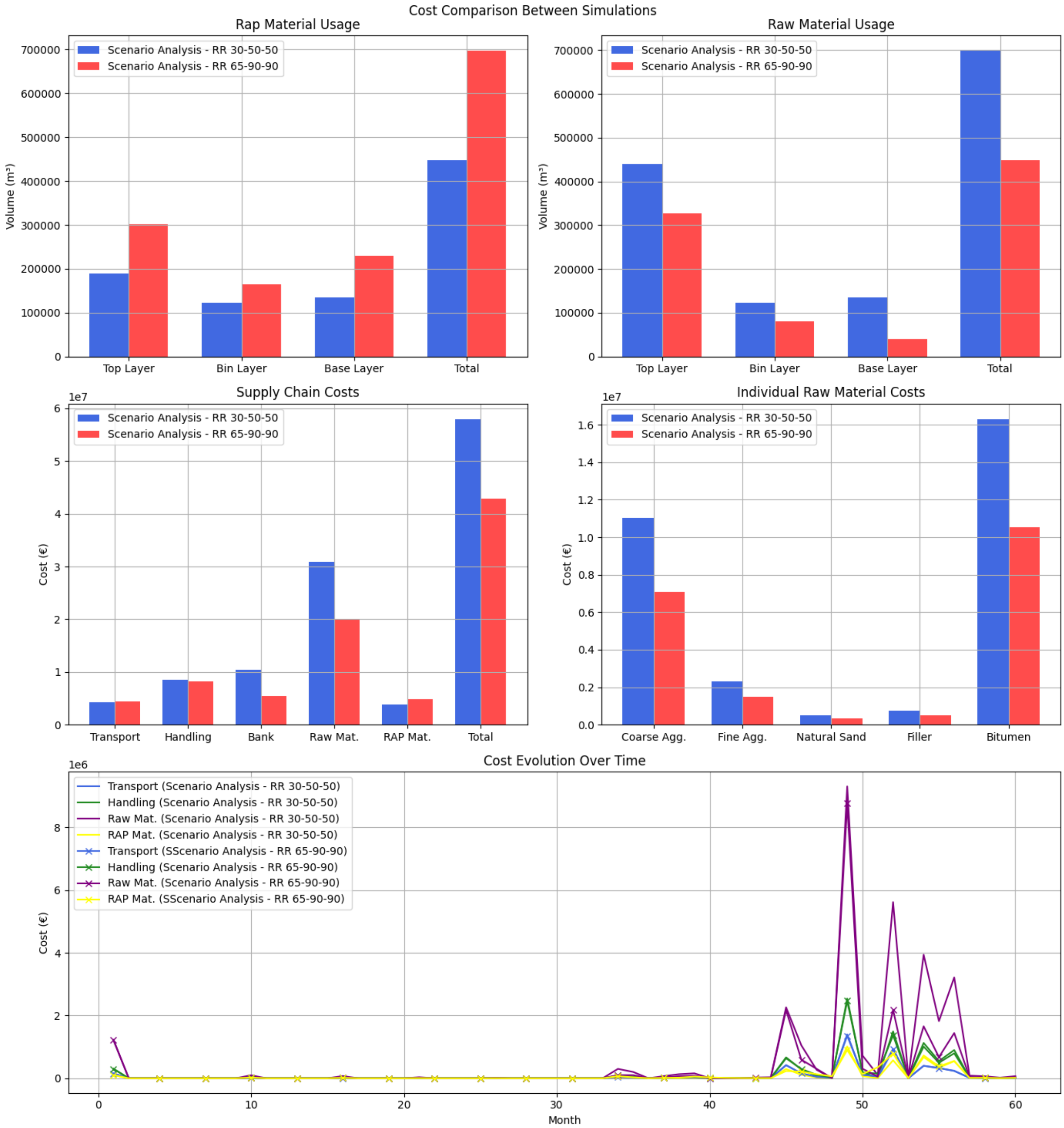

Figure 8.27: Comparing Supply Chain Cost and Raw Material Usage for the Minimum and Maximum Recycling Scenario Analysis.

Total Supply Chain Cost Analysis

The comparison of total supply chain costs between the minimum and maximum recycling scenarios reveals a significant difference. The total costs are €15,280,586 lower in the maximum recycling scenario, representing a reduction of 26.5%. This cost reduction is due to decreases in four of the five cost components:

- **Raw Material Costs**: Decreased by €11,037,378, a reduction of 35.9%.
- **Asphalt Bank Costs**: Decreased by €4,086,963, a reduction of 39.6%.
- **Handling Costs**: Decreased by €278,808, a reduction of 3.3%.
- **Transport Costs**: Decreased by €898,208, a reduction of 18.9%

In contrast, **RAP (Reclaimed Asphalt Pavement) Processing Costs** increased by €1,020,771, a growth of 26.3%.

The overall cost reduction can be explained by the increased allowance for asphalt recycling. Higher recycling rates lead to less RAP needing storage, a reduced asphalt bank size, decreased reliance on expensive raw materials, and increased RAP pre-processing. These factors explain the reduction in asphalt bank, raw material costs, and the rise in RAP processing costs. The smaller reductions in transport and handling costs are linked to the decreased purchase of new raw materials. In conclusion, higher permitted recycling rates significantly reduce costs, making high recycling scenarios more economically viable, especially when asphalt bank requirements are in place.

Raw Material Usage

There is a clear difference in raw material usage between the minimum and maximum recycling scenarios. In the minimum scenario, the overall recycling rate across all asphalt layers (surface, binder, and base) is 39.0%, while in the maximum scenario, it is 61.1%. The model applies these recycling percentages per scenario (minimum and maximum recycling scenario) as follows:

- **Surface Layer**: 30% in the minimum and 48.9% in the maximum scenario, with 30% and 65% recycling allowed, respectively.
- **Binder Layer**: 50% in the minimum and 67.3% in the maximum scenario, with 50% and 90% recycling allowed, respectively.
- **Base Layer**: 50% in the minimum and 83.7% in the maximum scenario, with 50% and 90% recycling allowed, respectively.

These figures suggest that the model's objective of minimising the total supply chain costs drives it to optimise the recycling percentages. In the context of the asphalt supply chain in the Amsterdam Transport Region, the optimal recycling percentages for cost minimisation align with those of the maximum recycling scenario. That also indicates that, with some adjustments, the model could potentially determine the economically optimal recycling percentages for any given supply chain scenario.

The following subsections provide additional information regarding the spatial and temporal dynamics of RAP and the storage of RAP in the asphalt banks, plus several noteworthy observations regarding asphalt production.

8.4.2.1 Recycling Rates and Its Effect on Asphalt Banks and the Spatial and Temporal Distribution of RAP

An analysis of the asphalt banks reveals that recycling percentages directly impact the size and location of an asphalt bank. Figure 8.28 highlights the two asphalt bank locations for the minimum and maximum recycling supply chain scenarios. In the minimum recycling scenario, Asphalt Bank 67 was selected, while in the maximum recycling scenario, Asphalt Bank 28 was chosen.

These asphalt banks are in different industrial areas. Asphalt Bank 28 is located in the Westhaven area of Amsterdam, near the four asphalt plants, while Asphalt Bank 67 is in the De Hemmes industrial area of Zaandam.

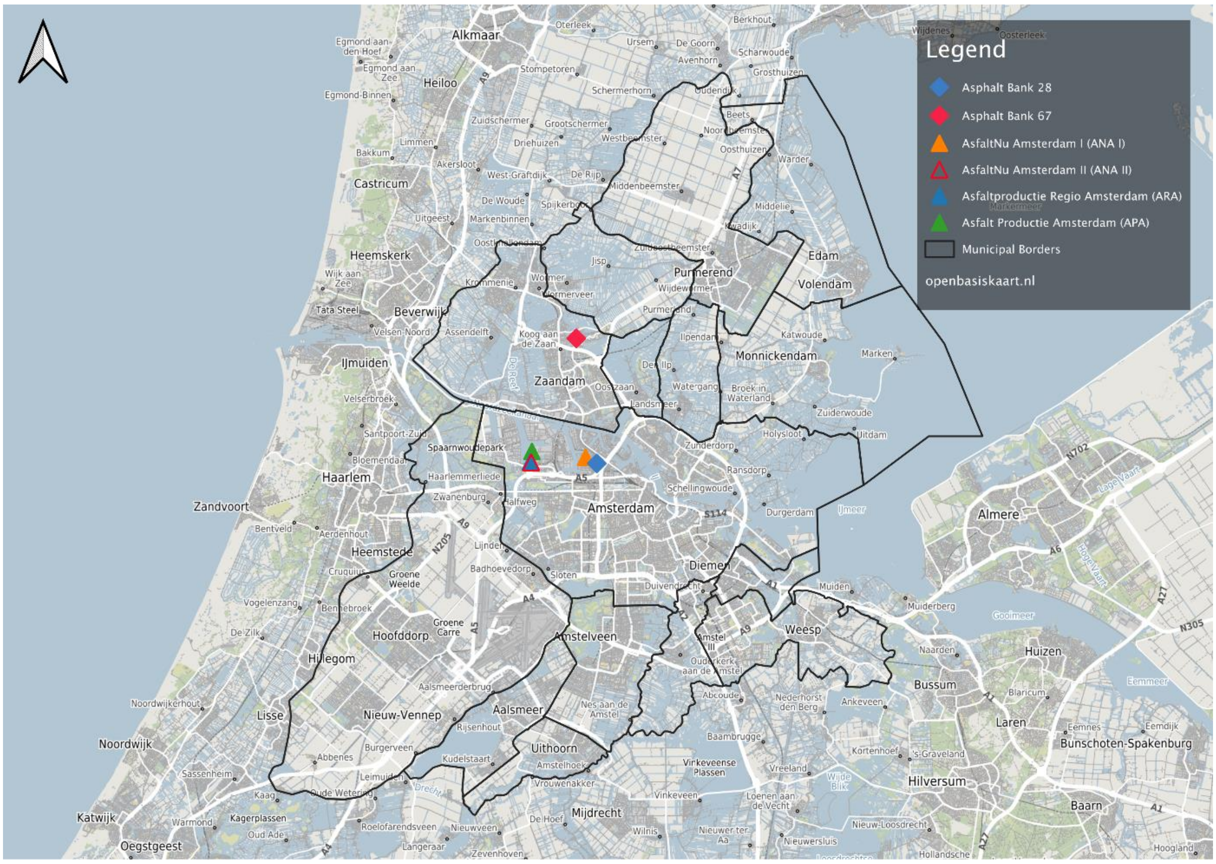

Figure 8.28: Location Candidate Asphalt Bank (28) and (67) for the Minimum and Maximum Recycling Scenario Analysis.

The asphalt banks differ significantly in size, a difference expected given that recycling percentages affect the flow rate of RAP and the required storage capacity.

In the minimum recycling scenario, less RAP can be reused, necessitating greater storage capacity. Figure 8.29 shows the progression of RAP storage levels and the storage capacity of Asphalt Bank 67, which has a capacity of 241,847 m³ due to the large amount of RAP that needs to be stored.

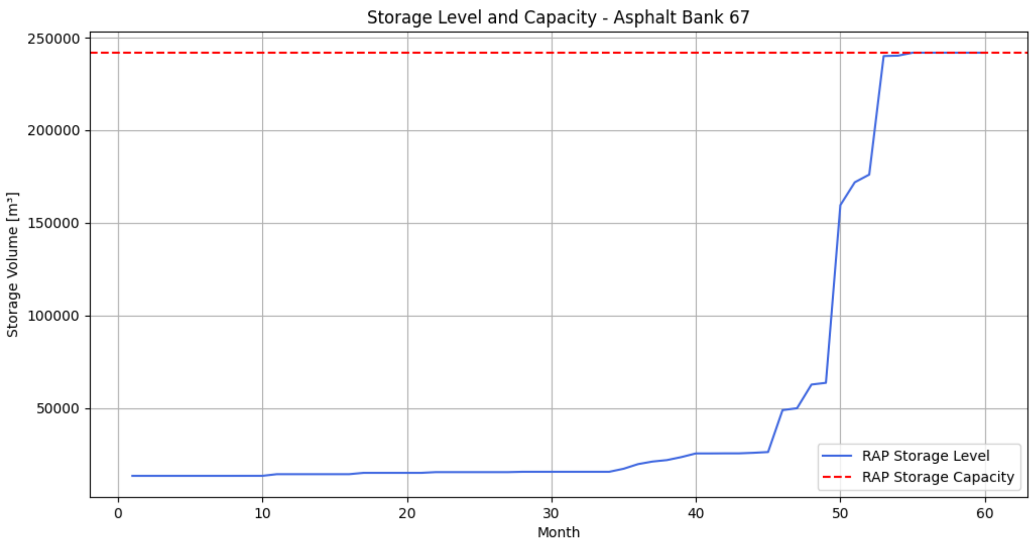

Figure 8.29: Storage Level and Capacity Asphalt Bank (67) for the Minimum Recycling Scenario.

In contrast, the maximum recycling scenario allows for more RAP reuse, resulting in faster throughput and reducing the need for storage. Figure 8.30 illustrates the RAP storage levels and capacity of Asphalt Bank 28, which is smaller than Asphalt Bank 67, with a capacity of 123,897 m³.

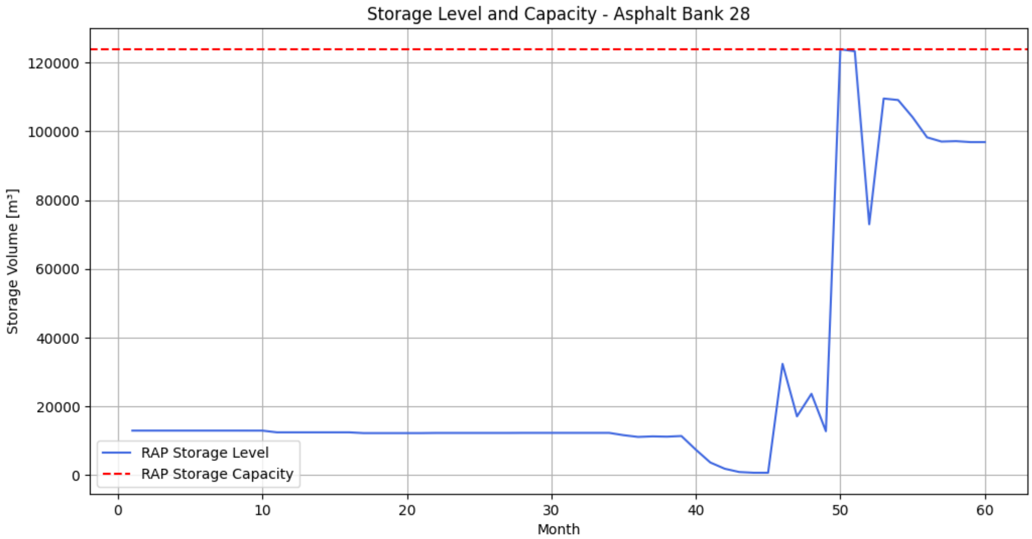

Figure 8.30: Storage Level and Capacity Asphalt Bank (28) for the Maximum Recycling Scenario.

Comparing the two scenarios reveals a pattern: the size of the asphalt bank, determined by the RAP flow rate (which depends on the permitted recycling rate and asphalt demand), influences the asphalt bank's location. As the asphalt bank reaches a particular size, it is economically advantageous to move from the relatively cheaper location of Asphalt Bank 67 to the more expensive location of Asphalt Bank 28. The scenarios show that below a particular asphalt bank capacity or size, the higher land costs at a closer, more expensive location are offset by decreasing transport costs, making it more cost-effective to position the asphalt bank nearer to the asphalt plants.

8.4.2.2 The Effect of Recycling Rates on Asphalt Production

Although the sensitivity analyses primarily focus on overall costs, asphalt banks, and the spatial and temporal distribution of RAP, the recycling rates influence the materials used in the asphalt production process and the individual production process by the asphalt plants, which warrants a brief examination.

The production data from two of the four asphalt plants, namely Asfalt Productie Amsterdam (APA) BV and AsfaltNu Amsterdam II (ANA II), were selected to function as an example. The production data from ARA Asfaltproductie Regio Amsterdam BV shows similar trends to the data of APA, and the data from AsfaltNu Amsterdam (ANA I) shows comparable trends to the data of ANA II.

When comparing the production data of APA (see Figure 8.31) and ANA II (see Figure 8.32), two trends emerge as a result of adjusting the recycling rates in the minimum and maximum recycling scenarios. In the maximum recycling scenario, asphalt production at APA (and ARA) decreases. Conversely, asphalt production at ANA II (and ANA I) increases in the maximum recycling scenario. The difference in production quantities between the scenarios is due to the location of the asphalt bank. In one scenario, the bank is closer to APA and ARA. And in the other scenario, it is closer to ANA I and ANA II. The model minimises the transport costs by increasing the production at the asphalt plants nearest to the asphalt bank.

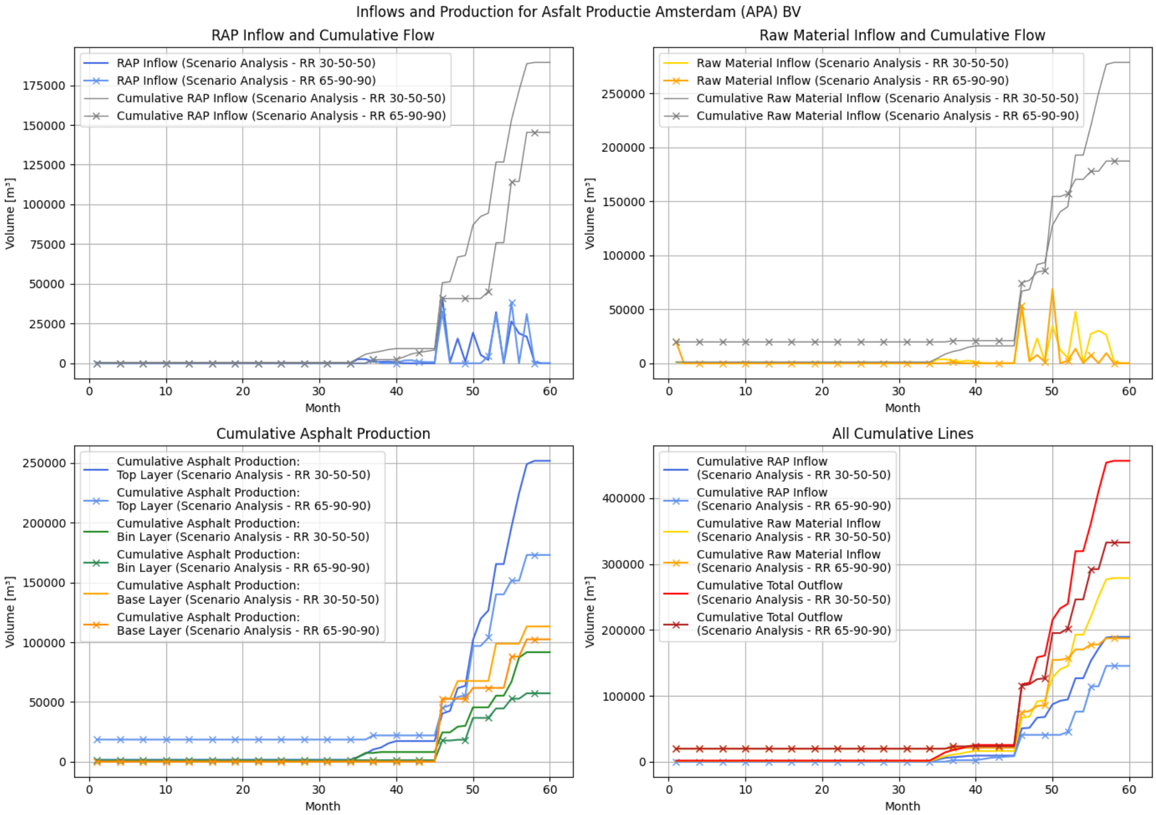

Figure 8.31: Comparison of Asphalt Production APA for the Minimum and Maximum Recycling Scenario Analysis.

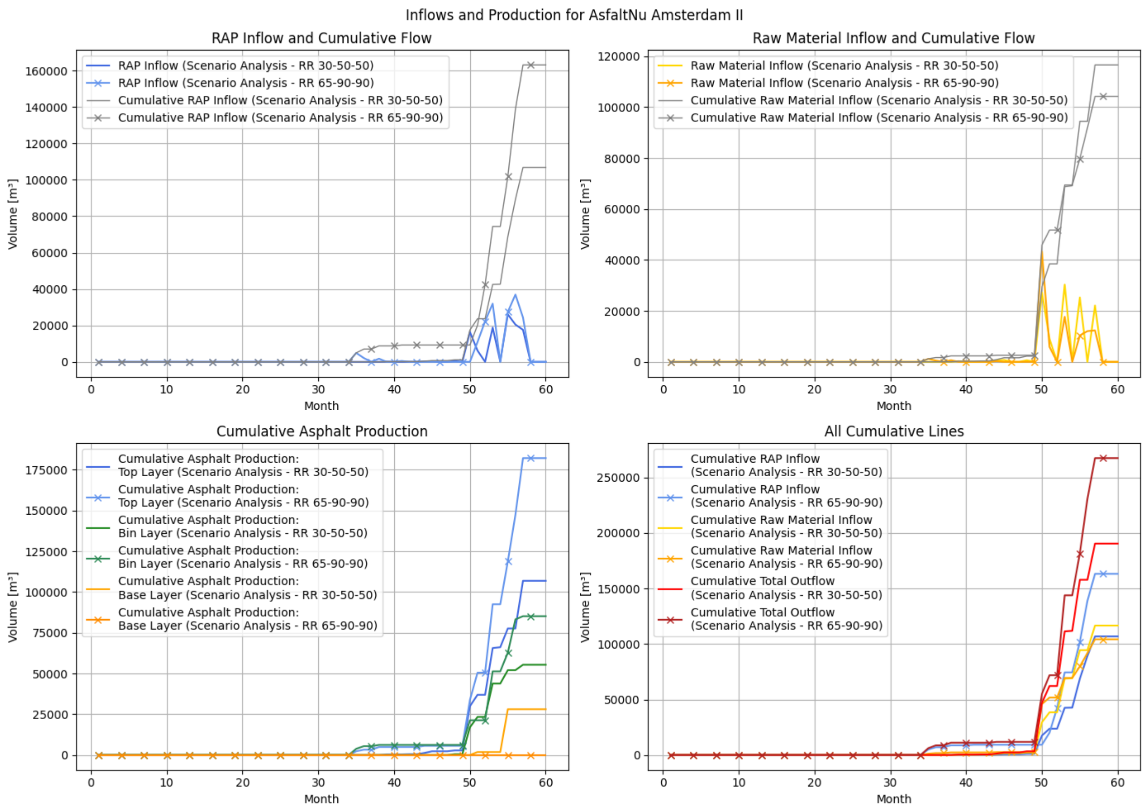

Figure 8.32: Comparison of Asphalt Production ANA II for the Minimum and Maximum Recycling Scenario Analysis.

Additionally, the production data of ANA II (Figure 8.32) clearly shows that the intake of RAP material is higher in the maximum recycling scenario compared to the minimum recycling scenario. That is due to the higher asphalt production and recycling percentage. Despite the increase in asphalt production, the intake of new raw materials is lower in the maximum recycling scenario than in the minimum recycling scenario - a logical outcome given the higher reuse rate, which reduces the need for new raw materials.

8.5 Summary of the Findings

A brief review of the key findings is essential before the chapter's conclusion. Table 8.1 highlights these results, offering a clear foundation for the chapter's closing insights.

Table 8.1: Overview of Results of Case Studies and Sensitivity Analysis.

Optimising the Asphalt Supply Chain with Asphalt Banks *Current vs. Future Scenarios & Sensitivity Analysis*

1. Key Costs Takeaways
• **Increased Costs:**
  o **Current Scenario with Asphalt Bank:** Total supply chain costs increase by **€10.96M** over five years compared to the supply chain without an asphalt bank.
  o **Future Scenario with Asphalt Bank:** Total supply chain costs increase by **€16.32M** over five years compared to the current scenario with an asphalt bank.
• **Future Cost Efficiency:** Despite higher costs, the future supply chain is more efficient with a **31.7%** cost increase vs. a **57.8%** production increase.
• **Multiple Asphalt Banks:** Optimising the number of asphalt banks could significantly reduce transport costs and overall supply chain expenses.

2. Cost Breakdown: Current vs. Future
Case Study 1: Current with Asphalt Bank
• **Total Cost Increase:** €10,961,926
• **Major Cost Drivers:**
  o Asphalt Bank: +€6.89M
  o Transport: +€1.12M
  o Handling: +€1.39M
  o Raw Material: +€970k
  o RAP Pre-processing: +€593k
Case Study 2: Future with Asphalt Bank
• **Total Cost Increase:** €16,326,804
• **Major Cost Drivers:**
  o Transport: +€2.56M
  o Handling: +€4.52M
  o Raw Material: +€5.28M
  o RAP Pre-processing: +€3.19M
  o Asphalt Bank Expansion: +€774k

3. Recycling Rate Comparisons **Current Scenario With and Without an Asphalt Bank (percentage RAP reuse):** • **Surface Layer:** 28.5% (With Bank) vs. 30% (Without Bank) • **Binder Layer:** 65.6% (With Bank) vs. 70% (Without Bank) • **Base Layers:** 70% (With and Without Bank) **Future Scenario (percentage RAP reuse):** • **Surface Layer:** 57.7% • **Binder Layer:** 58.1% • **Base Layer:** 61.1%

4. Asphalt Bank Optimisation

Multiple Banks (4):

- **Total Supply Chain Cost Reduction:** €649k over five years (1.3% decrease).
- **Transport Costs:** Reduced by €787k (18.1% decrease).
- **Asphalt Bank Costs:** Increased by €131k (1.9% increase).

5. Impact of Asphalt Bank on Supply Chain

- **Pros:** Optimises storage, transport, and RAP processing.
- **Cons:** Raises overall costs.

6. Sensitivity Analysis Insights

a. RAP Availability & Asphalt Demand

- **Low RAP Supply & High Demand (S&D 20 – 80):**
  - **Recycle Rates:** 25.4% (Surface), 47.1% (Binder), 37.9% (Base).
  - **Costs:**
    - Higher Raw Material Costs
    - Lower Storage Costs
    - Higher Handling costs
    - Lower transport costs
- **High RAP Supply & Low Demand (S&D 60 – 40):**
  - **Recycle Rates:** 30% (Surface), 70% (Binder & Base).
  - **Costs:**
    - Lower Raw Material Costs
    - Higher RAP processing Costs
    - Higher transport costs

b. Asphalt Recycling Rates

- **Minimum Recycling (RR 30 – 50 – 50):**
  - **Total Supply Chain Cost:** €57.99M
  - **Recycling Rates:** 39.0% overall
- **Maximum Recycling (RR 65-90-90):**
  - **Total Supply Chain Cost:** €42.91M (26.5% decrease)
  - **Recycling Rates:** 61.1% overall
  - **Breakdown Cost Reduction:**
    - Raw Material: -35.9%
    - Asphalt Bank: -39.6%
    - Handling: -3.3%
    - Transport: -18.9%
    - RAP Processing: +26.3%
- **Conclusion:** Higher recycling rates substantially reduce total supply chain costs, making high recycling scenarios economically more viable for asphalt banks despite increased RAP processing costs.

8.6 Conclusion

The results in this chapter provide a comprehensive exploration of the current and future asphalt supply chain, emphasising the potential impact of asphalt banks on economic performance and resource efficiency. Through detailed case studies and scenario analyses, the findings underscore the complexity and multifaceted nature of managing RAP in the asphalt supply chain.

Key insights reveal that while introducing asphalt banks significantly increases total supply chain costs, these facilities also offer strategic benefits, such as optimising RAP processing and storage and improving the long-term cost efficiency of asphalt production. The comparison between the current and future scenarios further highlights the importance of integrating higher recycling rates to enhance economic and potential environmental outcomes despite the associated logistical challenges.

Sensitivity analyses have shown that the use of multiple asphalt banks can slightly reduce costs by optimising the spatial and temporal dynamics of RAP. However, achieving these benefits requires careful planning to address the trade-offs between cost efficiency, resource allocation, and logistical coordination. The findings also suggest that higher rates are economically viable, aligning with broader sustainability goals.

In conclusion, this chapter demonstrates that asphalt banks play a critical role in optimising the asphalt supply chain, especially in a future context where higher recycling rates and increased road maintenance are anticipated. The results provide valuable insights for policymakers and industry stakeholders, highlighting the need for strategic planning and adoption of advanced recycling practices to ensure a resilient and sustainable asphalt supply chain.

9 Discussion

The case studies and sensitivity analyses provide critical insights into the spatial and temporal dynamics of the asphalt supply chain, especially regarding the potential impact of an asphalt bank. These findings revealed expected and unforeseen outcomes, underscoring the complexities inherent to the application of the MILP model and the programmed asphalt supply chain that it optimises. This chapter discusses the results, offering a comprehensive understanding of the underlying factors that influence the economic and logistical aspects of the asphalt supply chain.

9.1 Case Study 1: The Current Asphalt Supply Chain With and Without an Asphalt Bank

9.1.1 Economic Impact of an Asphalt Bank

One of the most striking results from the case studies is the significant increase in total supply chain costs due to the introduction of an asphalt bank. In Case Study 1, the transport costs increased by €1,119,167, handling costs rose by €1,385,336, raw material costs were €970,089 higher, and RAP pre-processing expenses rose by €593,208. Consequently, the total supply chain costs of the asphalt supply chain with an asphalt bank are €4,067,802 higher over five years. However, these costs do not account for the acquisition of the asphalt bank, which amounts to €6,894,124. Including the acquisition costs, the total supply costs for the supply chain with an asphalt bank are €10,961,926 higher than the scenario without an asphalt bank.

The rise in raw material costs was initially unexpected, revealing the complex interplay within the programmed supply chain. The assumption was that introducing an asphalt bank would maximise the use of RAP as it is significantly cheaper than using raw materials. However, the additional transport and handling costs required to move the RAP material from the asphalt bank to the asphalt plant were unaccounted for. As the model minimises the total supply chain costs, it finds an optimal situation where more raw materials are used compared to a supply chain without an asphalt bank to prevent incurring the higher costs for transporting, handling and pre-processing RAP material. In hindsight, this result shows that a sensitivity analysis where the price of the raw material increases could be very interesting. It also underscores the necessity of considering the direct and indirect costs when evaluating the financial viability of an asphalt bank.

9.1.2 Impact of an Asphalt Bank on Recycling Rates and Raw Material Usage

The introduction of an asphalt bank affects both recycling rates and raw material usage, as seen in the raw material cost increase discussed in section 9.1.1, Economic Impact of an Asphalt Bank. The base scenario, without an asphalt bank, maximises the reuse of RAP material, as it is a cheaper alternative to raw materials. Additionally, unused RAP must be stored at "temporary storage facilities" at the maintenance site, which incurs extra handling costs. As the model aims to minimise the total supply chain cost, it tries to prevent storing RAP material at these temporary sites, maximising recycling in the base scenario. In contrast, the asphalt bank scenario resulted in lower recycling rates, higher raw material usage, and increased costs.

This divergence suggests that while an asphalt bank centralises and potentially optimises RAP storage, it does not necessarily improve recycling rates from an economic standpoint. That is because the associated transport and handling costs are higher. Since the model prioritises minimising costs, it favours using raw materials when RAP handling, transport, and processing are more expensive. That observation may highlight a trade-off between cost efficiency and recycling in supply chain management.

9.1.3 Impact of an Asphalt Bank on the Spatial and Temporal Dynamics of RAP

The results also reveal significant differences in RAP's spatial and temporal dynamics between the scenarios with and without an asphalt bank. The base scenario relies on temporary storage facilities, which, while offering flexibility, lead to scattered storage of RAP material and extra material handling. In contrast, the asphalt bank scenario centralises RAP storage at specific locations, such as Asphalt Bank 67. This centralisation offers logistical advantages but also introduces higher associated costs.

9.2 Case Study 2: The Current and Future Asphalt Supply Chain With an Asphalt Bank

9.2.1 The Impact of a Future Scenario on the Total Supply Chain Costs

In the future asphalt supply chain with an asphalt bank, the total supply chain costs continue to increase. The 31.7% rise in total supply chain costs is due to a 57.8% increase in asphalt production, which indicates that higher recycling rates can enhance cost efficiency over time. As the total asphalt production increases more significantly as the total supply chain cost, it can be stated that the production of one cubic metre of asphalt becomes more cost-efficient, probably due to improved recycling rates. This finding suggests that increasing recycling practices can mitigate some of the cost increases associated with asphalt banks.

9.2.2 RAP Processing and Storage Dynamics in the Future Scenario

The future scenario also highlights the increased demand for RAP processing due to high recycling rates. Interestingly, despite the increased demand, the capacity requirement for the asphalt bank only rises marginally (3.8%), indicating that better recycling practices can reduce the need for extensive storage capacity. This result shows the importance of optimising RAP throughput to balance storage needs and cost efficiency.

9.2.3 Spatial Dynamics of Asphalt Banks in the Future Scenario

The future scenario also shows a shift in the spatial distribution of the asphalt banks, with the new location of Asphalt Bank 76 to optimise logistics and handle larger volumes of recycled material. This relocation highlights the critical role of the strategic placement of an asphalt bank in managing the cost and efficiency of the asphalt supply chain. This change also clearly shows that the location of release and the amount of RAP released influence the location of the asphalt bank.

9.3 Scenario Analysis of the Asphalt Supply Chain With an Asphalt Bank

9.3.1 Cost Optimisation by Multiple Asphalt Banks

The sensitivity analysis reveals that employing multiple asphalt banks can reduce overall supply chain costs by 1.3%, primarily through lower transport costs. This strategy also implies environmental benefits, such as reduced CO2 due to reduced transport. Multiple asphalt banks decrease transportation costs by keeping RAP within smaller areas and not moving it across the Amsterdam Transport Region, reducing transport distances and, thus, costs.

9.3.2 Impact of Recycling Rates on Asphalt Bank and Supply Chain Efficiency

Higher recycling rates drastically reduce total supply chain costs by 26.5%, mainly through decreased reliance on raw materials and smaller asphalt banks. The alignment of optimising the recycling percentages, as in the maximum recycling scenario, suggests that significant reuse of RAP is economically viable.

9.3.3 Impact on Asphalt Production by Asphalt Bank Location

The sensitivity analysis demonstrates that the location of asphalt banks affects asphalt production at individual asphalt plants. Asphalt plants closer to the asphalt bank benefit slightly from the model's objective to minimise the total supply chain costs, as lowering the transport costs results in the model moving more RAP to the nearest asphalt plants. To achieve maximum RAP transport to the nearest asphalt plants, the asphalt recycling rates at these plants are higher than the average. This finding underscores the impact of the location of an asphalt bank on asphalt production and efficiency.

9.4 Limitations

The discussed research results should be considered within the research limitations. These include:

- The findings are contingent upon the cost components considered within the model. There are likely other relevant costs, like the operational cost of the asphalt bank and management cost, excluded and could significantly affect the overall cost structure. As such, while the results provide a valuable foundation for understanding the economic impact of an asphalt bank, they should be viewed as part of a broader cost analysis that includes these additional factors.
- Secondly, excluding certain costs - such as the management expenses associated with the asphalt bank - limits the precision of the cost comparison. Without these, the financial assessment may be incomplete.
- Thirdly, the current study lacks a cost sensitivity analysis. It would be relevant to analyse how differentiations in raw material costs influence the model decision-making and the results, or more comprehensively, how all five cost components influence the decision-making and results.
- The results are also shaped by the scope and design of the model. For example, achieving the high recycling rates suggested (65% recycling in asphalt surface layers) may not be practically feasible without additional data on the RAP material about the crushed stone class, bitumen type, and material fraction.[§] The model does not fully address this, leaving questions about the practical cost efficiency of such high recycling rates.
- While the model indicates that increased recycling could reduce storage needs, reflecting the importance of RAP management, it does not sufficiently account for the practical challenges of managing higher volumes of RAP. Issues such as potential bottlenecks in processing capacity could undermine the effectiveness of this strategy or increase processing costs.
- The simulation period used in the model also influences significant decisions, such as the optimal location of the asphalt bank. A different time frame could alter maintenance schedules, locations, and the amount of RAP material released. That suggests that the ideal location for an asphalt bank is very dependent on specific temporal and geographic contexts.
- Moreover, the model covers only five years. It would be interesting to extend the analysis over a longer time horizon to explore scenarios in which multiple asphalt banks might be required. For example, if one asphalt bank experiences a shortage, could another within the Amsterdam Transport Region compensate? The feasibility of staffing and finding industrial space for multiple asphalt banks, which the model does not consider, could heavily impact their practicality.

[§] Crushed stone class, bitumen type, and material fraction are key factors tested before RAP material is reused in high-quality surface layers in the Netherlands. Crushed stone class (1 to 3) indicates quality, with class 3 allowed in surface layers. Bitumen type matters, as Polymer Modified Bitumen (PMBs), cannot be reused in asphalt with Penetration Grade Bitumen (PEN). The material fraction is also critical for reuse in high-quality asphalt.

- Additionally, the model assumes an availability of RAP material that may not reflect real-world conditions. It also overlooks the importance of RAP quality and suitability for reuse in specific asphalt layers, critically in practice.
- Finally, the model's ability to optimise which asphalt plant produces asphalt for specific maintenance locations does not fully reflect real-world procurement processes. Tendering and supply chain management are influenced by multiple circumstances and agents, and the model's reliance on this variable may skew the results. Further refinement is necessary to better align the model with practical tendering and supply chain realities.

In conclusion, while the model offers valuable insights, its limitations highlight the need for further research and refinement to ensure that the findings are applicable in real-world contexts.

10 Conclusion

This research sought to explore the impact of a regional asphalt bank on the spatial and temporal dynamics of RAP material flows within the Amsterdam Transport Region. A combination of tools and methodologies - an inventory analysis, interviews, and a Mixed Integer Linear Programming (MILP) model - was used to address these research questions. These tools and methodologies systematically uncovered insights into RAP release, asphalt market dynamics, and the effects on the spatial and temporal distribution of RAP within the asphalt supply chain of the Amsterdam Transport Region.

The central research questions were as follows:

- *(Main)* - What is the impact of a regional asphalt bank on the RAP material stock in the Amsterdam Transport Region?

The establishment of a regional asphalt bank would have a significant positive impact on the RAP material stock. The asphalt bank would centralise the storage and distribution of RAP, making it unnecessary to store amounts in temporary locations or sell to traders, thus maintaining a closed-loop asphalt supply chain. This centralisation would minimise RAP losses from the system and allow for efficient and structured use of RAP by the region's asphalt plants. The asphalt bank would serve as the key player in regulating RAP flow, ensuring that excess material is stored centrally and made available when needed.

- *(Sub-question 1)* - How is in-use asphalt mixture stock potentially released within the next five years, geographically distributed in the current road network of the Amsterdam Transport Region?

The release of in-use asphalt stock (i.e., RAP) within the next five years mainly depends on the timing of road maintenance activities, which are variable and hard to predict. Maintenance decisions are based on periodic inspections and the severity of road damage, which directly influence the timing and volume of RAP release. Current maintenance mainly focuses on the top and binder layers, with minimal contribution from the base layer, as the latter is often still in good condition. However, an increase in base layer replacement is expected in the coming years as these layers approach their end-of-life stage, altering the current pattern of RAP release. The release of RAP within the Amsterdam Transport Region over the next five years will primarily come from the top and binder layers, the locations and quantities depending on maintenance inspections and strategies in the region.

- *(Sub-question 2)* - What are the asphalt market dynamics of RAP materials considering the four asphalt plants in the Amsterdam Transport Region?

The RAP market in the Amsterdam Transport Region is highly competitive, with the four asphalt plants treating RAP as a valuable resource. Typically, the company or partnership that wins a maintenance tender retains the RAP for reuse and does not exchange it with its competitors. If the RAP storage capacity at the asphalt plant is limited, alternative storage solutions are sought, such as temporary storage at the construction site or other permitted locations. Only in rare cases, when no other options are available, is RAP sold to traders. This competitive environment makes it difficult for RAP material to circulate freely between asphalt plants, reinforcing the need for a centralised solution like an asphalt bank.

- *(Sub-question 3)* – What are the effects of a regional asphalt bank on the RAP material stocks at the four asphalt plants and the spatial distribution in the Amsterdam Transport Region over time?

A regional asphalt bank would centralise RAP storage, making surplus RAP material stored temporarily at asphalt plants or other locations unnecessary. By acting as the central intake and distribution point for RAP, the bank would facilitate the more efficient use of RAP by the asphalt plants, enabling them to access material when needed without directly trading with competitors. That would result in a more balanced and efficient spatial distribution of RAP stocks across the region over time. The centralised system would also allow for better management and sorting of RAP, ensuring optimal recycling and reuse in asphalt production.

11 Recommendations

Although the developed model already provides valuable insights into the asphalt supply chain with an asphalt bank, there are still opportunities for refinement and further research. These recommendations are categorised into two key audiences: **the scientific community** and **practitioners and policymakers**.

Recommendations for the Scientific Community:

- **Detailed Cost Components**: Expand the model to include additional cost components, such as energy consumption, labour costs, and resource depletion rates. That will allow for a more comprehensive cost-benefit analysis. These elements will also enhance the theoretical foundation and applicability of the optimisation model in the asphalt supply chain.
- **Refinement of Slack Penalty Factors**[**]: Remove or refine slack penalty factors that currently simplify the model but may not fully represent real-world uncertainties. By utilising more sophisticated slack variables, researchers can improve the model's realism and reliability, which can lead to better predictive power of the optimisation model.
- **Incorporation of Uncertainty and Stochastic Optimisation**: Recognise the existence of various uncertainties within the asphalt supply chain, including demand variability, supply disruptions, material availability, and transportation delays. Future research should adopt a stochastic optimisation approach to handle these uncertainties. That would provide more robust solutions by accounting for uncertainty in model inputs, leading to optimised decision-making under uncertain conditions.
- **Environmental Impact Metrics**: Incorporate environmental impact metrics, such as the MKI (Environmental Cost Indicator), alongside cost minimisation. Researchers can expand the model by considering a multi-objective optimisation approach that considers both environmental and economic factors, contributing to developing more sustainable asphalt supply chain models in the scientific literature.
- **RAP Material Differentiation by Layer**: Differentiate RAP materials by layer (surface, binder, and base). This distinction better reflects real-world practices and provides the scientific community with an enhanced model capable of addressing more granular details on the asphalt supply chain. By studying this differentiation, future research can help optimise the reuse of RAP in specific applications.
- **Asphalt Production Process Details**: Incorporate specific production processes for different asphalt layers. That will increase the model's complexity but provide a higher detail, offering more realistic representations of production dynamics. This recommendation encourages further research on the relationship between production methods and their impact on the supply chain.
- **Realistic Transport Limitations**: Introduce transportation constraints based on vehicle capacities, allowable distances, and traffic regulations to improve model accuracy. These practical constraints align the model's asphalt logistics better with current infrastructure and regulatory limitations.
- **Asphalt Bank Refinement**: Refine the asphalt bank model to sort RAP into specific types and fractions, aligning with actual industry practices. That would allow us to explore more effective strategies for recycling and reusing RAP materials.

[**] Appendix VIII – Model Design Considerations, paragraph 7.6 Slack Penalties, provides additional information about the slack penalty factors.

- **Tender Process Optimisation**: Simulate a more realistic tender process by pre-selecting asphalt plants for specific tenders. That reflects actual market conditions and allows researchers to explore supply chain efficiency and competition.

Recommendations for Practitioners and Policymakers:

- **Integration of Asphalt Banks into the Supply Chain**: When integrating an asphalt bank into the supply chain, the number and location of these asphalt banks should be guided by regional demand patterns, proximity to construction sites, and logistical efficiency. In high-density urban areas such as the Amsterdam Transport Region, a distribution network of smaller asphalt banks might be more effective, reducing transportation costs and emissions. In less populated regions, a centralised asphalt bank may be more efficient.
- **Supply Chain Reorganisation for Maximising Benefits**: To fully exploit the benefits of an asphalt bank, it is essential to reorganise the supply chain to prioritise RAP collection, sorting, and redistribution. That requires integrating asphalt banks into tender processes, with clear procurement guidelines for reusing RAP materials. A coordinated effort between clients, contractors, and asphalt plants is necessary to optimise the supply chain. Such coordination should focus on streamlining logistics, minimising transport distances, and consistent RAP availability.
- **Ownership and Responsibility for RAP Management**: A key consideration for policymakers is determining who should take responsibility for released RAP material. A potential solution is to assign ownership to the public entity, which could manage asphalt banks and enforce regulations of RAP use. Alternatively, a public-private partnership (PPP) model could incentivise private parties to manage asphalt banks under specific environmental and efficiency criteria. This approach could ensure cost-effectiveness and adherence to sustainability goals.
- **Business Model for Asphalt Banks**: The business model for asphalt banks should incentivise RAP material reuse. Policymakers can introduce financial incentives for companies actively reusing RAP material. In addition, a tender-based system that rewards companies prioritising RAP use could further enhance the adoption of asphalt banks.
- **Environmental Policy and Regulatory Framework**: Requiring contractors to report on their use of recycled materials and adopt sustainable practices within the supply chain would help drive compliance. Establishing a regulatory framework that mandates a certain percentage of RAP usage in public tenders would further promote the adoption of asphalt banks and contribute to achieving sustainability targets.
- **Guidelines for Tender Processes and Contracts**: The tendering process should be adapted to account for asphalt bank integration. That could involve pre-selecting asphalt plants having access to RAP materials or implementing a qualification system favouring contractors with higher RAP usage in previous projects. Additionally, introducing long-term contracts for asphalt supply and recycling would provide companies with the certainty they need to invest in infrastructure related to RAP processing and asphalt banks.
- **Regional Collaboration and Knowledge Sharing**: Collaboration across regions is vital for standardising the use of asphalt banks. Policymakers should encourage knowledge sharing between road authorities, contractors, asphalt plants, and research institutions to ensure the continuous improvement of RAP reuse and asphalt bank operations. Establishing a national knowledge database could enhance the overall efficiency of the supply chain and increase the quality of recycled asphalt.

While the current model provides a solid foundation for understanding the impact of a regional asphalt bank, the recommendations offer distinct pathways for both **the scientific community** and **practitioners and policymakers**. For researchers, the focus is on refining theoretical models, while for industry professionals and policymakers, the aim is to improve practical implementation and sustainability. Implementing these recommendations will significantly contribute to improving the efficiency and environmental sustainability of the asphalt supply chain, particularly in the Amsterdam Transport Region.

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13 Appendices

Appendix I – Maps Amsterdam Transport Region

Appendix II – Coding Methodology Road Network

Appendix III – Road Topology Data

Appendix IV – Asphalt Supply Chain Analysis

Appendix V – Interview Methodology

Appendix VI – Interview Questions

Appendix VII – Interview Results

Appendix VIII – Model Design Considerations