



Optimising spatial implications of circular paving flows through road maintenance planning and design in the city of Rotterdam.

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Room for Reuse: Optimising spatial implications of circular paving flows in the city of Rotterdam

Cover Image

Road renovation Soetendaalseweg (Own Photo)

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The AI tool ChatGPT (OpenAI, 2025 version) was used solely as a supportive instrument during the writing process of this thesis. It assisted the author in checking spelling, grammar, sentence structure, and clarity of expression. No parts of this thesis were generated by AI. All analyses, arguments, and written content were fully produced and verified by the author.

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Preface

This thesis marks the conclusion of my master's degree in Metropolitan Analysis, Design and Engineering. Over the past ten months, I have explored how circularity in urban infrastructure is not only a technical or environmental challenge, but also a question of organisation and logistics. Conducting this research in collaboration with the Municipality of Rotterdam allowed me to connect analytical methods with the realities of municipal practice, a process that has challenged and enriched my understanding of how circular ambitions take shape in everyday work.

My motivation for this research stemmed from an ongoing curiosity about the circular transition and its connection to how cities function. In many ways, this thesis became an attempt to translate that curiosity into something concrete: to quantify the space that circular ambitions require, and to understand why such space is often missing. Throughout this work I learned that research within a municipal context rarely follows a linear path. Working with fragmented data, evolving policies, and many dedicated people taught me to approach circularity as a process of coordination rather than control, and to value progress over perfection.

I am deeply grateful for the opportunity to conduct this research within the Municipality of Rotterdam. Thank you for allowing me to shape the direction of the project and for providing access to data, facilities, and a stimulating work environment. I believe this collaboration has generated valuable insights. Special thanks go to my company supervisor, Rik de Nooijer, for his guidance and for providing new perspectives that helped me refine the direction of this research. My appreciation also extends to all municipal colleagues who shared their time and perspectives during interviews and discussions, your openness was essential to this project.

I would also like to thank my academic supervisors, Dr. Karel van den Berghe and Dr. Jaco Quist, for their constructive feedback while giving me the freedom to steer the research in my own direction. I greatly appreciated their insights, which helped me refine the scope of this thesis and maintain focus on its practical relevance.

Finally, I would like to thank my family and friends for their patience, encouragement, and many thoughtful conversations. You reminded me to step away from the screen, take a moment, and return with fresh perspective.

Writing this thesis has been both demanding and rewarding. It reminded me that progress often begins by making better use of what already exists.

I hope you enjoy reading through this thesis.

Milo Marler

Rotterdam, October 2025

Executive Summary

Global resource consumption continues to rise, driving climate change, biodiversity loss, and pollution. High-income countries such as the Netherlands play a disproportionate role in this trend, with per-capita material footprints far exceeding sustainable limits. In response, the Dutch government aims to halve the use of primary abiotic resources by 2030 and achieve full circularity by 2050. Yet, despite these ambitions, the translation of circular economy targets into local infrastructure practice remains limited, and the spatial implications of circularity are still poorly understood. As one of the most resource-intensive domains of the built environment, urban road infrastructure illustrates this gap. Municipalities, as key managers of road networks, must reduce material throughput while accommodating the spatial demand that circular practices create. This thesis addresses this challenge by examining how Rotterdam's road renovation practices can enable the systematic reuse of paving materials and manage the resulting spatial implications.

The transition to a circular infrastructure sector can be viewed through the Multi-Level Perspective, which explains systemic change as the interaction between niche innovations, stabilised regimes, and broader landscape pressures. In the Dutch road sector, this regime is characterised by standardised procurement, risk-averse asset management, and entrenched norms of compliance and predictability. Growing landscape pressures from resource scarcity, climate targets, and European policy increasingly push the sector to experiment with circular practices. The reuse of modular paving materials illustrates a circular strategy that is technically feasible yet institutionally constrained by linear routines, fragmented responsibilities, and limited logistics infrastructure. Recent literature recognises that circularity is not only a technical but also a spatial challenge, as recovery, storage, and redistribution depend on physical space. However, most studies focus on the building sector, offering little insight into how circularity manifests in infrastructure systems such as roads, and in particular, how much space is required to store and process secondary paving materials under realistic municipal conditions.

To address this gap, the research employs an embedded mixed-methods design that combines quantitative and qualitative components. A material flow analysis quantifies the circular flows of paving materials within Rotterdam's planned road renovations and estimates the resulting spatial demand for storage and processing infrastructure. Complementary qualitative analysis of municipal policy documents and expert interviews examined how planning and design frameworks shape these material dynamics, while site visits to reuse facilities helped define what constitutes reuse infrastructure for road pavements and determine their associated spatial requirements.

The results reveal how Rotterdam's circular ambitions are shaped by the interaction between technical planning cycles and institutional design frameworks. Road planning, defined by long-term maintenance schedules linked to sewer replacement and subsidence, determines the pace and sequence of material release. Design regulation prescribes uniform materials to ensure visual and functional consistency. While this standardisation enables reuse by promoting dimensional compatibility, it simultaneously constrains circularity by excluding older or non-standard materials from reapplication. As a result, between 84 and 93 percent of technically reusable materials can be reintegrated into new projects.

The division between standard and non-standard materials defines two distinct forms of reuse infrastructure in Rotterdam, each with specific spatial requirements. Storage hubs are used for pre-palletised, standardised paving materials that can be stored compactly for reuse in upcoming projects, with a spatial demand of 618 - 684 m². By contrast, construction hubs handle non-standard materials that require sorting, cleaning, and mixing before reapplication. Because these materials are less in demand, they accumulate as surpluses that require disproportionate storage space, ranging between 5,869 - 8,306 m².

To explore how this spatial imbalance could be reduced, three adjustment pathways were modelled: adjustments in project planning, adjustments in project design, and a combination of both. The results show that design-oriented adjustments, in particular broadening the application of non-standard materials to greener or less visually sensitive areas, provide the most substantial improvement. This approach reduces the spatial demand for construction hubs by up to 80%, while simultaneously lowering virgin material consumption and associated emissions. In contrast, planning adjustments have limited effect, as maintenance schedules are closely tied to sewer replacement and subsidence, leaving little flexibility to synchronise projects for more balanced material flows.

The study concludes that achieving circular efficiency in municipal infrastructure requires a balanced approach between physical capacity, adaptive design regulations, and institutional coordination. While sufficient storage capacity is a precondition for sustained reuse, its effectiveness depends on design flexibility that allows the reusable material stock to be reintegrated into new projects. Standardisation remains valuable for ensuring quality and compatibility, yet it must evolve to accommodate older materials rather than exclude them. Methodologically, the combined use of material flow and spatial analysis offers a transferable framework for other municipalities: local authorities can reproduce this approach, provided that data on material stocks, road maintenance cycles, and design standards are available, to anticipate the spatial implications of circular transition within their own infrastructure systems.

Managementsamenvatting

Het wereldwijde grondstoffengebruik blijft toenemen en draagt bij aan klimaatverandering, biodiversiteitsverlies en milieuvervuiling. Hoge-inkomenslanden zoals Nederland spelen hierin een onevenredig grote rol, met materiaalvoetafdrukken per hoofd van de bevolking die de duurzame grenzen ruim overschrijden. Als reactie hierop streeft de Nederlandse overheid ernaar het gebruik van primaire abiotische grondstoffen in 2030 te halveren en in 2050 volledige circulariteit te bereiken. Ondanks deze ambities blijft de vertaling van circulaire doelstellingen naar de lokale infrastructuurpraktijk beperkt, en zijn de ruimtelijke implicaties van circulariteit nog nauwelijks onderzocht. De stedelijke weginfrastructuur vormt een duidelijk voorbeeld van dit vraagstuk: gemeenten moeten het materiaalverbruik terugdringen en tegelijkertijd omgaan met de ruimtelijke vraag die hergebruik met zich meebrengt. Dit onderzoek richt zich op de vraag hoe de wegvervangingspraktijk in Rotterdam kan bijdragen aan systematisch hergebruik van bestratingsmaterialen en hoe de daarbij behorende ruimtelijke gevolgen kunnen worden beheerst.

De transitie naar een circulaire infrastructuursector kan worden begrepen aan de hand van het Multi-Level Perspective, waarin systeemverandering ontstaat uit interacties tussen niche-innovaties, gevestigde regimes en bredere landschapsdrukken. In de Nederlandse weginfrastructuur wordt dit regime gekenmerkt door gestandaardiseerde aanbesteding, risicomijdend beheer en sterke normen van voorspelbaarheid en naleving. Toenemende druk vanuit grondstoffenschaarste, klimaatdoelstellingen en Europees beleid zet de sector aan tot experimenten met circulaire werkwijzen. Het hergebruik van secundaire elementenverharding is daarvan een voorbeeld: technisch haalbaar, maar institutioneel belemmerd door lineaire routines, gefragmenteerde verantwoordelijkheden en een gebrek aan opslag- en verwerkingsinfrastructuur. Recente literatuur benadrukt dat circulariteit niet alleen een technische, maar ook een ruimtelijke opgave is, omdat terugwinning, opslag en herverdeling fysieke ruimte vereisen. Toch richt bestaand onderzoek zich voornamelijk op materialen uit gebouwen en biedt het weinig inzicht in de manier waarop circulariteit zich manifesteert binnen infrastructuursystemen zoals wegen, en in het bijzonder hoeveel ruimte nodig is om secundaire bestratingsmaterialen op te slaan en te verwerken binnen gemeentelijke kaders.

Om deze kennislacune te adresseren, is een geïntegreerde mixed-methodsaanpak toegepast, waarin kwantitatieve en kwalitatieve methoden zijn gecombineerd. Een materiaalstroomanalyse is gebruikt om de circulaire stromen van elementenverharding te kwantificeren binnen de geplande wegvervangingsprojecten van Rotterdam en berekende de daaruit voortkomende ruimtelijke vraag naar opslag- en verwerkingsinfrastructuur. Aanvullende kwalitatieve analyse van gemeentelijke beleidsdocumenten en expertinterviews bracht in kaart hoe ontwerp- en planningskaders deze materiaalstromen beïnvloeden, terwijl locatiebezoeken aan hergebruikfaciliteiten hielpen om hergebruikinfrastructuur voor elementenverharding te definiëren en de bijbehorende ruimtelijke eisen te bepalen.

De resultaten laten zien dat de circulaire ambities van Rotterdam worden bepaald door de samenwerking tussen technische planningscycli en institutionele ontwerpkaders. Wegplanning, gebaseerd op langetermijnonderhoudsschema's gekoppeld aan rioolvervanging en bodemdaling, bepaalt het tempo en de volgorde waarin materialen vrijkomen. Ontwerpvoorschriften schrijven uniforme materialen voor om visuele en functionele consistentie te waarborgen. Hoewel deze standaardisatie hergebruik bevordert door dimensionele compatibiliteit, beperkt zij tegelijk de circulariteit doordat oudere niet-standaard materialen worden uitgesloten van hergebruik. Hierdoor kan tussen de 84 en 93 procent van de technisch herbruikbare materialen opnieuw worden toegepast.

De verdeling tussen standaard- en niet-standaardmaterialen definieert twee vormen van hergebruikinfrastructuur, elk met een eigen ruimtelijke behoefte. Opslaghubs worden gebruikt voor gepalletiseerde standaardmaterialen die compact kunnen worden opgeslagen voor her-

gebruik in toekomstige projecten, met een ruimtebeslag van 618 - 684 m². Constructiehubs verwerken daarentegen niet-standaardmaterialen die extra bewerking vereisen, zoals sorteren, reinigen en mengen, en nemen hierdoor aanzienlijk meer ruimte in beslag: 5,869 - 8,306 m².

Om deze ruimtelijke disbalans te verkleinen, zijn drie aanpassingspaden gemodelleerd: wijzigingen in onderhoudsplanung, wijzigingen in wegontwerp en een combinatie van beide. De resultaten tonen aan dat ontwerpgerichte aanpassingen, het toelaten van niet-standaardmaterialen in groenere of visueel minder gevoelige gebieden, de grootste verbetering opleveren. Deze benadering vermindert de ruimtelijke vraag naar constructiehubs met tot wel 80%, terwijl ook het gebruik van primaire grondstoffen en de bijbehorende emissies afnemen. Planingsaanpassingen hebben daarentegen een beperkt effect, doordat onderhoudsschema's nauw verbonden zijn met rioolvervanging en bodemdaling, wat weinig ruimte laat voor afstemming tussen projecten.

Het onderzoek concludeert dat circulaire efficiëntie in gemeentelijke infrastructuur een evenwicht vereist tussen fysieke capaciteit, adaptieve ontwerprichtlijnen en institutionele coördinatie. Voldoende opslagcapaciteit is een randvoorwaarde voor materiaalhergebruik, maar de effectiviteit ervan hangt af van ontwerpflexibiliteit die het mogelijk maakt om de bestaande materiaalvoorraad opnieuw in te zetten. Standaardisatie blijft belangrijk om kwaliteit en compatibiliteit te waarborgen, maar moet zich ontwikkelen tot een systeem dat ook oudere materialen kan opnemen. Methodologisch biedt de combinatie van materiaalstroom- en ruimtelijke analyse een overdraagbaar kader voor andere gemeenten: mits gegevens over materiaalvoorraden, onderhoudscycli en ontwerprichtlijnen beschikbaar zijn, kunnen zij deze aanpak toepassen om de ruimtelijke consequenties van de circulaire transitie binnen hun eigen infrastructuresystemen te anticiperen.

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List of Abbreviations

Abbreviation	Definition
BSS	Betonstraatstenen (Concrete Paving Blocks)
BSS-non-RS	Niet Rotterdamse Stijl Betonstraatstenen (pre-1996, non-standardised, Concrete Paving Blocks)
BSS-RS GR	Grey Standard Concrete Paving Blocks
BSS-RS NE	Nesselande District Standard Concrete Paving Blocks
BSS-RS WB	Warm Brown Standard Concrete Paving Blocks
CBH	Circular Building Hub
CE	Circular Economy
CROW	Centre for Regulation and Research in Civil Engineering, Hydraulic Engineering, Road Construction and Traffic Engineering
I&W	Ministerie van Infrastructuur en Waterstaat (Ministry of Infrastructure and Water Management)
LEAB	Low Energy Asphalt Beton
MFA	Material Flow Analysis
MLP	Multi-Level Perspective
MRN	Main Road Network
Mt	Megaton
RAP	Reclaimed Asphalt Pavement
RS	Rotterdamse Stijl
SBS	Straatbakstenen (Brick Paving Blocks)
SDG	Sustainable Development Goal
SRN	Secondary Road Network

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Chapter 1

Introduction

The rapid rise in natural resource consumption drives climate change, biodiversity loss, and pollution. Over the past 50 years, global material use has tripled, and without intervention, resource extraction is projected to increase by 60% by 2060, exceeding sustainable limits (United Nations Environment Programme, 2024). High-income countries, such as the Netherlands, play a disproportionate role in this trend, with per capita consumption-related impacts up to six times greater than those of low-income nations. Much of this burden is externalized, affecting resource-rich low- and middle-income countries where extraction and production take place. To transition toward sustainability, high-income nations must reduce resource consumption, improve efficiency, and decouple economic growth from environmental degradation (Hanemaaijer et al., 2023).

Recognizing this challenge, the Netherlands has committed to halving primary abiotic resource use by 2030 and achieving a fully Circular Economy (CE) by 2050 (Rijksoverheid, 2023). However, despite these ambitions, the most recent data suggest that resource consumption in 2022 increased compared to 2020, highlighting the slow progress in implementation (Hanemaaijer et al., 2025). This stagnation highlights structural barriers to circularity across sectors, such as the built environment, which accounts for 50% of raw material consumption in the Netherlands (Vervoordeldonk et al., 2021). Within this sector, infrastructure, encompassing roads, bridges, and public spaces, is especially resource-intensive. Specifically road maintenance and construction, which is responsible for 68% of emissions and consuming 17.75 megatons of materials annually, amounting to 10% of the country's total domestic material use (Fröhling & Van Driel, 2024).

The Dutch road infrastructure network spans 143.1 thousand kilometres, of which 123.5 thousand kilometres are under municipal management (CBS, 2024). This distribution underscores the pivotal role municipalities can play in advancing circular practices through strategic

procurement, maintenance, and redevelopment (Fröhling & Van Driel, 2024). Achieving circularity in road construction requires integrating principles such as circular design, high-quality asphalt recycling, increased use of secondary and biobased materials, and extending asset lifespans via predictive maintenance (Rijksoverheid, 2023). However, implementing these strategies requires additional physical space for localized material storage, processing, and manufacturing. These activities, in turn, depend on a logistics intensive network of distribution and processing facilities (Rood & Evenhuis, 2023).

1.1 Problem Statement

National targets to reduce raw material use increase the urgency to rethink how infrastructure systems are maintained and renewed. Yet the translation of these ambitions into local practice remains unclear. For municipalities, as the primary managers of road networks, this creates a challenge: they must both transform the way they work with material flows from road renovation and manage the spatial demand that is generated.

Without systematic insight into material flows, municipalities cannot adequately anticipate the spatial demand these flows create. Research on circularity in the built environment has largely focused on buildings, with attention to design for disassembly, reuse in replacement projects, and the organisation of flows within large housing portfolios. These approaches are typically confined to the scale of individual buildings or asset portfolios, where a single owner can align supply and demand more directly. Far less attention has been directed toward the integration of circular flows from other sectors, or to the local and regional scales where such flows intersect (Van Bueren et al., 2022). This gap is particularly evident in road infrastructure. Paving materials such as asphalt, bricks, and concrete form a significant share of the public material stock (Arnoldussen et al., 2022). While technically durable and reusable (Keijzer et al., 2015; Nusselder et al., 2020), these materials are often discarded due to limited storage, lack of planning alignment, or absence of incentives for reuse (Van Uden et al., 2025). In practice, this means that although paving materials could be reused at scale, municipalities lack the spatial and organisational infrastructure to make this a systematic reality.

The spatial dimension of circular practices remains poorly understood, even as the urgency of resource-efficient development grows. Circular operations such as material sorting, storage, repair, and remanufacturing require new spatial arrangements, yet their precise requirements remain undefined. Most existing assessments are qualitative, with little quantitative evidence on actual local or regional needs (Warringa et al., 2023). This lack of systematic spatial insight risks undermining circular ambitions, particularly in dense urban areas where land-use competition is high (Rood & Evenhuis, 2023). Traditionally, such operations have been located in industrial zones, but these zones are increasingly under pressure from housing, climate adaptation, and renewable energy infrastructure (Van den Berghe et al., 2024). As a result, municipalities struggle to safeguard space for logistics-intensive, low-value activities that are essential to local resource loops. Instruments such as spatial planning are therefore critical, as they allow municipalities not only to accommodate technical processes but also to organise the logistics on which circular material flows depend (Williams, 2020).

The city of Rotterdam illustrates this tension. As the Netherlands' second-largest city, it must reconcile ambitious sustainability targets with a resource-intensive physical environment. Civil infrastructure works, such as roads, quays, bridges, and public spaces, account for more than a third of the city's climate impact, primarily due to linear construction practices (Bruinsma & De Graaff, 2023). Although Rotterdam has formulated circular ambitions, including for its infrastructure, there is no integrated spatial strategy for facilitating circular material flows within this domain (Gemeente Rotterdam, 2023, 2024a, 2024b). Without a clear understanding of how road renovation practices shape material outflows, and how these flows in turn translate into spatial demand for reuse infrastructure, the municipality risks reinforcing existing linearity.

1.2 Research Aim

National ambitions for circular construction demand a better understanding of how material flows from infrastructure projects can be recovered and reintegrated at the local level. Yet municipalities currently lack systematic insight into how these flows interact with the spatial and organisational conditions of reuse. The absence of such insight risks undermining circular objectives, especially in dense cities where available space for logistics and storage is limited. This thesis addresses this gap by examining how Rotterdam's existing design and planning frameworks influence the scale of paving material reuse and the spatial demand this generates.

To address these questions, the study develops and applies an integrated approach that combines qualitative analysis of current road renovation practices and reuse infrastructure with a quantitative assessment of circular material flows. This embedded mixed-methods design offers a structured way to operationalise circularity challenges in road maintenance and provides insights relevant to urban planning.

1.3 Research Questions

To support the municipality of Rotterdam in advancing its circular ambitions the central research question investigated in this thesis is as follows:

How do Rotterdam's road renovation practices enable the systematic reuse of paving materials while managing the spatial demand this creates?

To answer the research question, three sub-questions have been defined:

Sub-Research Question 1: *How do Rotterdam's current road renovation practices and reuse ambitions shape the scale and composition of circular paving material flows?*

Sub-Research Question 2: *What is the spatial demand of reuse infrastructure under Rotterdam's current road renovation practices?*

Sub-Research Question 3: *In what ways can Rotterdam's road renovation practices be adjusted to optimise paving material reuse and its associated spatial demand?*

By focusing on these questions, the study systematically examines the relationship between road renovation practices, circular material flows, and their spatial implications within Rotterdam.

1.4 Relevance to Urban Practice

Municipalities in the Netherlands have become pivotal in advancing circular practices within public space. Whereas paving materials from street or park renovations were traditionally discarded and replaced with new ones (Marée, 2025), many local governments are developing reuse-oriented policies and experimenting with local recovery and storage facilities. Larger municipalities such as Amsterdam and Utrecht have already made substantial progress (Keuchenius, 2025; Wichgers, 2025), while smaller cities like Haarlem and Apeldoorn are also formulating circular strategies (Regioedactie Haarlem, 2024; SEB, 2025). A common development in these efforts is the emergence of municipal reuse infrastructure, where secondary materials are collected, sorted, and prepared for reapplication in public works. Such facilities mark a shift in how municipalities approach material management, turning circularity into a spatial and organisational planning task rather than solely a technical or procurement challenge.

Circular management of paving materials intersects with several broader sustainability goals, particularly those captured in the United Nations' Sustainable Development Goals (SDGs) framework (Ogunmakinde et al., 2022). It relates to SDG 8 (decent work and economic growth), SDG 11 (sustainable cities and communities), SDG 12 (responsible consumption and production), and SDG 15 (life on land). By clarifying how circular material systems within municipal infrastructure depend on spatial, logistical, and governance conditions, such approaches sup-

port the creation of more resource-efficient and liveable metropolitan regions. These dynamics are increasingly relevant for cities worldwide, where limited space, infrastructure renewal, and resource scarcity jointly define the scope for sustainable urban development.

1.5 Reading Guide

This thesis is structured into eight chapters Chapter 2 develops the theoretical foundation for this thesis. It introduces the concept of the circular economy and situates it within broader sustainability transitions, focusing on its implications for the Dutch road infrastructure sector. Chapter 3 outlines the methodology, introducing the case of Rotterdam and describing how the embedded mixed-methods design addresses the three sub-research questions. Chapters 4 to 6 present the results, addressing the three sub-research questions in sequence. Chapter 7 discusses the findings and reflects on them in relation to the theory and methods used, while Chapter 8 concludes by answering the main research question and provides recommendations for Rotterdam's urban policy, other municipalities, and further research.

Chapter 2

Literature Review

The global prevailing economic system follows a linear take-make-dispose model, where resources are extracted, used, and discarded with minimal reintegration. Historically, this model thrived on cheap raw materials and expensive labour, driving industrial growth. However, with resource depletion and increasing global demand, supply chains are under growing strain. Escalating raw material expenses and growing competition further weaken economic resilience. As industrialized nations near resource capacity limits, the sustainability of this model is increasingly questioned, prompting a shift toward regenerative economic systems such as CE (Sariatli, 2017).

Emerging in the 1970s, the CE was introduced to address resource depletion and economic instability, challenging the linear model. By the 1980s and 1990s, it gained traction in policy and business, evolving into a systemic approach to decouple economic growth from resource consumption (Stahel, 2020). Despite growing adoption among scholars and practitioners, its definition remains highly debated. Kirchherr et al. (2023) analysed 221 definitions, finding that the CE is increasingly seen as a regenerative system requiring systemic changes in supply chains and production. Its core principles focus on waste reduction, value retention, and decoupling economic activity from finite resources. Rather than an end in itself, the circular CE serves as a pathway to sustainability, integrating environmental quality, economic development, and social equity.

A widely accepted definition comes from the Ellen MacArthur Foundation (n.d.), which describes CE as “a system where materials never become waste and nature is regenerated. In a CE, products and materials are kept in circulation through processes like maintenance, reuse, refurbishment, remanufacture, recycling, and composting. The CE tackles climate change and other global challenges, like biodiversity loss, waste, and pollution, by decoupling economic activity from the consumption of finite resources.”

A structured way to interpret and implement circularity is through the use of R-strategies, which classify interventions that reduce resource use and increase material efficiency across the lifecycle of products and assets (Potting et al., 2016). Building on this, Hanemaaijer et al. (2023) distinguish four overarching strategic directions that guide circular practice, by grouping these, as illustrated in Figure 2.1. First, **Substitution** replaces finite resources with renewable, low-impact, or less environmentally harmful alternatives. Second, **Narrow the loop** focuses on reducing raw material input by avoiding unnecessary products, sharing existing assets, or manufacturing with fewer resources. Third, **Slow the loop** aims to extend product and component lifespans through reuse, repair, and remanufacturing. Finally, **Close the loop** seeks to prevent material leakage by recovering and recycling materials so that only truly unrecoverable waste is disposed of through incineration or landfilling.

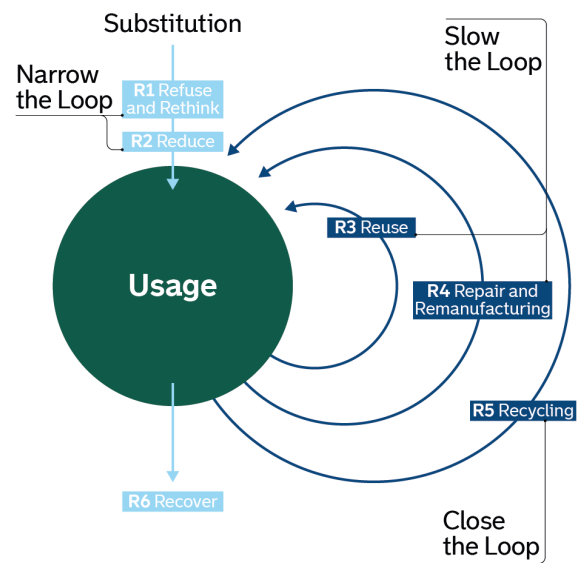


Figure 2.1 R-strategies grouped in looping categories. Adapted from Hanemaaijer et al. (2023).

2.1 The Circular Transition

As circularity has become a central objective in Dutch national policy (Rijksoverheid, 2023), it is supported by a coordinated set of policy instruments, time-bound targets, and institutional shifts (Coenen, 2024). Unlike traditional policy goals, this transition demands long-term commitment, cross-sectoral coordination, and systemic restructuring. It addresses so-called ‘wicked problems’ that are characterised by uncertainty, multiple actors, and conflicting interests (Coenen et al., 2023). Such challenges have increasingly been conceptualised as sustainability missions, goal-oriented, collective strategies aimed at addressing large-scale systemic problems, and are positioned within the broader domain of sustainability transitions (Kirchherr, Hartley, et al., 2023).

According to Köhler et al. (2019), sustainability transitions can be defined as fundamental shifts in societal systems such as energy, mobility, or food, needed to confront persistent environmental and social challenges. These transitions extend beyond incremental change or isolated technical innovation, involving complex transformations across technologies, behaviours, institutions, and infrastructures. To understand the dynamics of such transitions, Köhler et al. (2019) further discuss a range of theoretical frameworks that adopt a systemic lens to capture co-evolutionary complexity, as well as phenomena such as path-dependency, emergence, and non-linear dynamics.

One such framework is the multi-level perspective (MLP), in which Geels (2011) conceptualises transitions as the outcome of interactions across three analytical levels: niche innovations, socio-technical regimes, and the broader socio-technical landscape. **Regimes** are characterised by stabilised rules, institutional routines, and shared practices that coordinate actor behaviour and reinforce system stability. **Niches** function as protected spaces for alternative approaches and experiments, while the **landscape** refers to exogenous trends, such as climate policy, economic shifts, or cultural change, that shape pressures on the regime. Transitions occur when niche innovations gain momentum, landscape pressures destabilise the regime, and windows of opportunity open for systemic change.

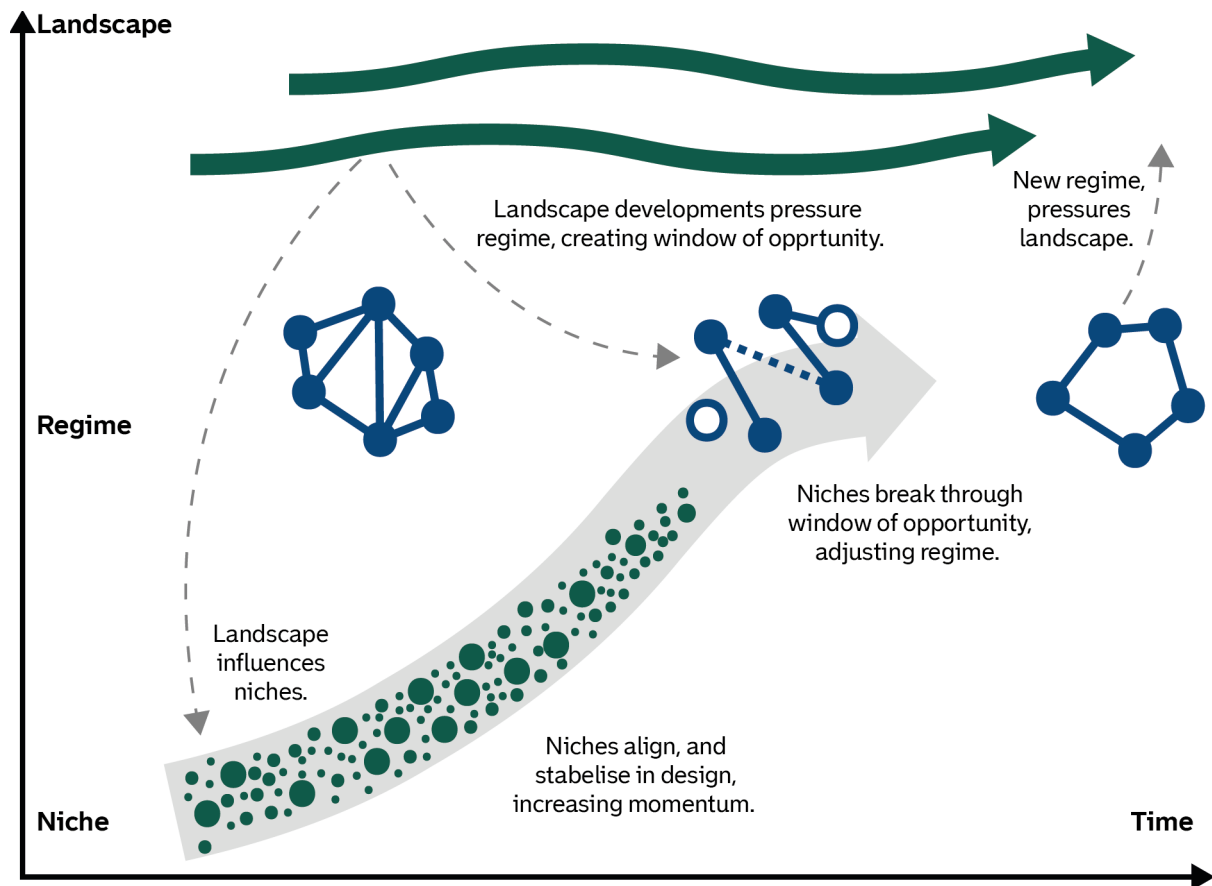


Figure 2.2 The multi-level perspective on transitions. Adapted from Geels (2011).

2.2 A Multi-Level Perspective on the Dutch Infrastructure Sector

While the field of sustainability transitions is broad, infrastructure, including road infrastructure, has been identified as a critical domain where circular ambitions intersect with entrenched socio-technical regimes. This sector represents a substantial material footprint and plays a significant role in meeting national resource reduction goals (Coenen, 2024). In this context, MLP offers a useful theoretical reference point for analysing how such sectors are shaped by stabilised regimes, influenced by broader landscape pressures, and opened up through local experimentation.

2.2.1 Socio-Technical Regime

The Dutch road infrastructure system comprises 143,085 km and is divided into two categories: the Main Road Network (MRN) and the Secondary Road Network (SRN). The MRN, which spans 13,659 km, includes all highways and is managed by Rijkswaterstaat (RWS) and the provinces. The SRN, at 129,427 km, consists of roads maintained primarily by municipalities (95%) and water boards (5%) (CBS, 2024). While the MRN is almost entirely paved with asphalt, the SRN exhibits greater material diversity, consisting of asphalt (60%) and *elementenverharding* (modular paving) (40%). This extensive use of modular paving, outside of historic city centres, is quite unique to the Netherlands, comprising *straatbakstenen* (SBS; brick paving blocks), which account for 11% of the SRN, and *betonstraatstenen* (BSS; concrete paving blocks), which account for 29% (Arnoldussen et al., 2022; Keijzer et al., 2015). The widespread use of these materials can be attributed to a combination of aesthetic, practical, and technical factors. Modular paving aligns well with the Dutch context: it allows surfaces to adapt to soil settlement, is less prone to cracking than continuous materials such as concrete or asphalt, and enables easy repair or replacement of small sections without large-scale reconstruction (CROW, 2021).

Safety considerations also play a role: driving over these blocks produces noise that increases with vehicle speed, discouraging drivers from exceeding speed limits (SWOV, 2019).

As network expansion has slowed due to spatial constraints, material flows in the sector are increasingly shaped by maintenance activities rather than new construction (Arnoldussen et al., 2022). Despite this shift, the institutional structure of the sector remains largely linear. In the Netherlands, the development and maintenance of public space are treated as distinct governmental responsibilities, resulting in a fragmented approach in which asset management is viewed primarily as the final phase of a spatial project (Brinkhuijsen et al., 2020). This separation is reinforced by the procedures through which projects are commissioned and delivered.

For municipalities, the development or renovation of road infrastructure is typically initiated through public procurement, defined as the acquisition of goods and services by government or public sector organizations (Ntsondé & Aggeri, 2021). As this procedure is legally required, standardized tendering procedures dictate how projects are commissioned and delivered, making procurement a central element of the sector's institutional structure (RVO, n.d.). These procedures ensure transparency and competition, but also reinforce a fragmented and risk-averse approach in which compliance with rules and cost control take precedence. Although procurement frameworks in principle allow public authorities to stimulate innovation and sustainability by embedding such criteria in tenders, empirical evidence shows that sustainability clauses are often weakly formulated or absent (Gelderman et al., 2024). As a result, project delivery tends to prioritize short-term compliance, while responsibilities for long-term performance are shifted to the management phase.

Urban management is responsible for infrastructure during the period of use, including interim reconstruction, and has its own organizational, management, and financial structure, with its reporting and accountability line for the governance. Urban management tasks begin when new assets are transferred to managers at the start of the use phase. Managers maintain assets, coordinate, and regulate the use of assets, and renew, refurbish, or replace assets as needed, due to aging, changes in the environment, and changing demands for public space (Said & Tempels, 2023). This institutional separation between procurement and management has direct implications for material use, as decisions on paving types and reuse options are made within a system that prioritises compliance over long-term environmental performance.

The environmental performance of road infrastructure is largely determined by the choice of paving materials, as their production causes the highest environmental impact throughout the pavement life cycle and significantly influences overall costs. The use of low-impact and secondary materials offers the greatest potential for reducing environmental burden (Zhao & Yang, 2023). Although advancements have been made in developing low-carbon alternatives, these materials have yet to be applied at scale in the Netherlands and secondary material use is largely limited to recycling (Arnoldussen et al., 2022).

For asphalt roads, recycling has been common practice for decades. Reclaimed Asphalt Pavement (RAP) is typically reintegrated into production via batch plants, using cold, warm, or hot mix techniques. In the Netherlands, hot and warm mix asphalt dominate due to strict quality requirements and regulatory standards. Hot mix asphalt typically consists of 95% aggregate and 5% bitumen and is widely used in large-scale applications such as roads and parking lots. Warm mix asphalt, while similar in composition and performance, is produced at lower temperatures, resulting in reduced energy use and emissions (Oliveira & Xavier Silva, 2022).

For brick and concrete paving blocks, secondary material use primarily involves the recovery of aggregates from construction and demolition waste. These are mixed with granulates from the wider built environment and applied in road foundations or for site elevation. With an annual volume of 4.5 Mt, this material stream represents the largest waste flow in the Dutch infrastructure sector (Arnoldussen et al., 2022). However, this practice constitutes a form of downcycling, in which materials are reused for applications of lower functional or economic value. Downcy-

2 Literature Review

clinging often results from contamination or dilution and can also be design-induced. These mechanisms reduce material quality and typically lead to three effects: increased thermodynamic effort for reprocessing, lower applicability of the recovered materials, and a loss of economic value (Helbig et al., 2022).

Together, these practices reflect the dominant socio-technical regime governing Dutch road infrastructure: focused on maintaining system performance through standardised practices and minimising technical and legal risks. While some circular principles are present in the form of recycling, the current regime largely reinforces material throughput and prioritises predictability and compliance over innovation.

2.2.2 Socio-Technical Landscape

The road infrastructure sector is increasingly shaped by exogenous pressures that originate beyond the immediate institutional boundaries of municipalities or asset managers. Haar (2024) notes that resource scarcity has become one of the most immediate drivers of change, as rising extraction costs, the depletion of reserves, and geopolitical instability make access to raw materials increasingly uncertain. At the same time, accelerating environmental degradation and the visible impacts of climate change have intensified both political and societal demands for sustainable alternatives. Together, these global developments are pushing governments to take a more active role in guiding economic and industrial transitions, as market mechanisms alone can no longer ensure stability or resilience.

Within Europe, these pressures have led to a common policy direction. One key initiative is the European Green Deal, launched in 2019, which aims to cut emissions by at least 50% by 2030, rising towards 55%, and establishes the goal of achieving climate neutrality by 2050 through the European Climate Law (European Commission, n.d.). Alongside the Green Deal, the European Commission adopted the Circular Economy Action Plan in 2020. Within this plan, the construction and building sector is identified as a key product value chain. For this sector, the Commission proposes to include recycled content requirements for certain building products, integrate lifecycle assessment into public procurement, and strengthen targets for material recovery in construction and demolition waste (European Commission, 2020). While these measures target the broader construction and building sector, they primarily focus on the building scale.

Following this European framework, national governments are expected to translate these goals into sector-specific strategies. The Dutch Ministry of Infrastructure and Water Management (I&W) translated these ambitions into a national strategy for climate-neutral and circular infrastructure projects. The strategy emphasizes that this transition requires close collaboration across all levels of government, as the combined climate impact of regional and local authorities is estimated to be four times greater than that of I&W itself (Ministerie van Infrastructuur en Waterstaat, 2020). To achieve the national targets, I&W and its executive agency RWS have developed a roadmap for road pavements that aims to reach net-zero emissions across the entire pavement lifecycle and halve the use of primary abiotic resources by 2030. The roadmap highlights the need for systemic change in procurement, innovation, and collaboration between public clients and contractors (Rijkswaterstaat & Ministerie van Infrastructuur en Waterstaat, 2022).

These landscape pressures collectively challenge the existing socio-technical regime governing Dutch road infrastructure. A system long defined by standardisation, risk aversion, and cost efficiency must now integrate circularity, experimentation, and cross-sector collaboration. Under growing policy and market pressure, the regime will need to adapt, shifting from maintaining performance within established routines to reconfiguring them in pursuit of systemic change.

2.2.3 Niche Innovations

Within MLP, technological and organisational change often begins in protected experimental spaces, or niches, where new practices can develop outside the constraints of established regimes. To identify such emerging niches within the infrastructure sector, a literature search was conducted in Scopus, focusing on peer-reviewed journal articles published between 2015 and 2025. The query circular AND infrastructure AND (road OR pavement OR asphalt OR concrete OR brick) was applied across the fields of engineering, environmental science, and social sciences, yielding 15,026 results. This broad dataset provided an overview of how circularity has been studied within infrastructure research. Titles and abstracts were manually screened to isolate studies that specifically addressed road infrastructure and paving materials, as these represent a significant share of material flows within the built environment. Within this subset, most publications focused on technical aspects, such as material performance, recyclability, and environmental assessments, whereas relatively few examined the application strategic circularity frameworks in road construction and maintenance.

The results of this review indicate that circular experimentation in road infrastructure primarily manifests through technological innovation. The strategies defined by Hanemaaijer et al. (2023) provide a useful lens to categorise these developments, showing how different paving types enable distinct circular pathways. These innovations can therefore be interpreted as niche experiments aligned with one or more R-strategies. Substitution targets the material footprint by introducing low-impact or renewable alternatives. Narrowing the loop involves optimising material use through design or preventive maintenance. Slowing the loop emphasises reuse practices, particularly for elements like concrete and brick paving. Closing the loop focuses on improving recycling practices to retain material value.

Table 2.1 Overview of circular innovations in road infrastructure.

Strategy	Paving Material	Innovation	Source
Substitution	Asphalt	LEAB (Low Energy Asphalt Concrete)	Arnoldussen et al. (2022); BAM (2023); Keijzer et al. (2015)
		Lignin as bio-based binder	Moretti et al. (2022); Oliveira & Xavier Silva (2022)
	Concrete paving block	Geopolymer concrete	Ikotun et al. (2024); Shehata et al. (2022); Yoo et al. (2024)
	Brick paving block	Energy-neutral brick production	Besier & Marsidi (2020)
Narrow the loop	Asphalt	In-situ rejuvenation	Liu et al. (2025)
	All types	Predictive maintenance with AI	Chen et al. (2021)
Slow the loop	Concrete and brick paving block	Accounting for material reuse rates	Keijzer et al. (2015); Nusselder et al. (2020)
	All types	Material passports	Leindecker et al. (2025)
Close the loop	Concrete and brick paving block	Increasing closed-loop recycling	Pallewatta et al. (2023); Zhang et al. (2018)

To illustrate how these niches are emerging in practice, Table 2.1 summarises a selection of recent developments across these categories, specifying pavement type, innovation type, and source. The reviewed innovations vary in maturity and implementation. Some, such as low-energy asphalt (LEAB), material passports, and in-situ rejuvenation, are already applied in Dutch practice, while the reuse of paving materials through municipal initiatives has recently

gained increasing attention. Others, including lignin-based asphalt, geopolymer concrete, and low-energy brick production, are in pilot phases, whereas AI-based predictive maintenance remains in the early stages of development. This diversity in maturity reflects the different stages of niche development within a regime that remains predominantly linear. A more detailed elaboration of each example is provided in Appendix A.

While these innovations illustrate growing momentum for circular experimentation within the road infrastructure sector, their impact remains largely confined to isolated pilots. Most developments aim to optimise existing materials or construction methods, but are rarely translated into governing practices or embedded in standard procedures. As a result, these experiments often fail to move beyond the pilot stage, limiting their influence on how projects are commissioned, managed, and evaluated.

2.2.4 Transition Dynamics

Building on the previous sections, where the regime's linear procurement and asset routines (2.3), the mounting landscape pressures (2.4), and the emergence of niche innovations (2.5) were outlined, this section brings these dynamics together. Landscape developments, most notably resource scarcity, regulatory tightening, and climate policy (Haar, 2024), are beginning to unsettle established routines that long prioritised cost control and compliance (Gelderman et al., 2024; Said & Tempels, 2023). As environmental criteria are increasingly embedded in tendering and performance management, prompting public bodies to reconsider risk-averse commissioning. This gradual shift opens limited space for experimentation and inter-organisational learning within a regime that remains primarily geared toward throughput and predictability.

Against this backdrop, niche innovations in road infrastructure extend material lifespans, reduce energy use, and reconfigure supply chains around secondary resources. Yet their system-wide impact remains modest. Despite national ambitions and growing project activity, most practices operate in isolation and struggle to translate into regime-level change. The barriers differ by circular strategy:

- **Substitution:** Sustainable alternatives face exclusion in tenders due to absent validation, limited long-term performance data, and non-aligned standards, favouring conventional options that fit existing guidelines and risk frameworks (Coenen et al., 2023).
- **Narrow the loop:** Technical options exist but stall through institutional inertia, unclear responsibilities, and weak integration between asset management and design; lacking metrics (e.g., distance-to-target) undermines legitimacy in decision routines (Coenen et al., 2023; Said & Tempels, 2023).
- **Close the loop:** High-value recovery is constrained by legal, logistical, and financial systems optimised for linear flows; projects remain structurally dependent on open-loop outputs such as secondary aggregates (Arnoldussen et al., 2022; Coenen et al., 2023).

Compared to the other circular strategies, the **Slow the loop** approach, specifically material reuse, appears conceptually more straightforward, as it involves materials that have already proven their technical reliability and are relatively inexpensive because they are already owned. However, despite these advantages, it proves especially difficult to implement within the current regime. Public procurement frameworks rarely support reuse, and designing with secondary components is operationally challenging due to the absence of dedicated logistical infrastructure (Coenen et al., 2023; Van Uden et al., 2025).

2.3 Spatial Frameworks for Reuse in Infrastructure

The difficulties surrounding material reuse reflect a broader misalignment between circular ambitions and the way public infrastructure systems are currently organised. Material reuse requires coordination across design, demolition, and procurement processes that are not yet

intended to operate in closed loops. Moreover, it introduces logistical and spatial challenges that existing asset management frameworks do not yet accommodate. These structural barriers have prompted researchers and practitioners to explore alternative ways of organising and governing material flows. Recent conceptual developments therefore focus on how reuse can be spatially, institutionally, and operationally embedded within the urban context.

When waste is reframed as a resource, and outputs are expected to re-enter construction processes, linear value chains evolve into what Van den Berghe & Verhagen (2021) describe as re-supply chains, as illustrated for modular paving in Figure 2.3. In these systems, the same site can act as both supplier and consumer of materials, producing recoverable elements during demolition and demanding them again during new construction. Because supply and demand rarely coincide in time or specification, remanufacturing functions as a bridge between these temporal and technical gaps, converting reclaimed materials into usable inputs and linking demolition, processing, and construction into one continuous cycle. This process forms the operational basis of circular resource use in the built environment.

Translating the principle of a re-supply chain into practice requires more than aligning technical processes; it demands a reconfiguration of the spatial organisation of material flows. Furlan et al. (2022) introduce the concept of territorialising circularity, emphasising that reuse must be rooted in place rather than managed as an abstract logistics network. In this view, territory acts as an enabling structure that shapes how efficiently materials can circulate. Resource sheds emerge as operational sites where secondary materials are stored, processed, and redistributed as new inputs. Their location depends on the intensity and direction of material flows, proximity to infrastructure, and the availability of space for processing and temporary storage. Instead of following administrative borders, these resource sheds reflect functional interdependencies within the urban material system.

Within the construction industry, resource sheds are increasingly operationalised through Circular Building Hubs (CBHs), locations where clusters of circular companies exchange resources and knowledge, or where waste is stored, processed, and redistributed as secondary materials (Tsui et al., 2024; Van Uden et al., 2025). Tsui et al. (2024) distinguish four main types: urban mining hubs, industry hubs, craft centres, and local material banks, each defined by spatial parameters such as proximity to construction sites, infrastructure access, and available storage capacity. Despite growing interest, the concept remains underdefined and empirically limited. Van Uden et al. (2025) identify persistent challenges related to upscaling, shared ownership, and the inclusion of hub use in tenders, alongside the absence of robust data infrastructures. They argue that CBHs represent an intermediate step rather than a final model: as digital systems and procurement standards increasingly accommodate reuse, leaving physical hubs to evolve into lighter logistical facilities or disappear where regime practices no longer require them.

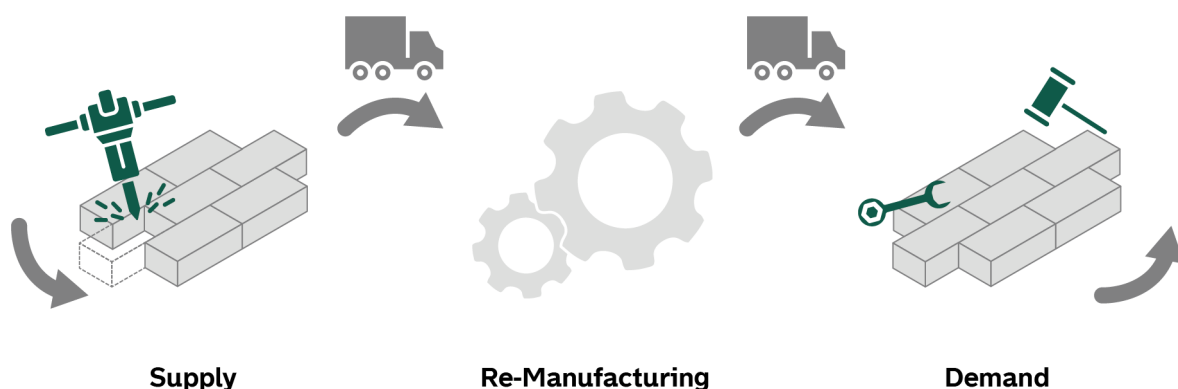


Figure 2.3 The re-supply chain for paving materials. Adapted from Van den Berghe & Verhagen (2021).

2.4 Knowledge Gap

Although the transition to a circular economy (CE) has been widely examined across sectors, its operationalisation in road infrastructure remains constrained by entrenched socio-technical regimes and fragmented governance structures (Coenen, 2024; Coenen et al., 2023; Geels, 2011). Numerous circular innovations have emerged across the strategies of substitution, narrowing, slowing, and closing the loop (Hanemaaijer et al., 2023), yet their integration into infrastructure practice remains limited. These developments are often studied in isolation, with limited attention to the spatial and institutional configurations that determine their feasibility in practice (Coenen et al., 2023).

The reuse of secondary modular paving materials is particularly underdeveloped in both theory and practice. While reuse is conceptually embedded within CE frameworks and supported by national and EU policy (European Commission, n.d., 2020; Ministerie van Infrastructuur en Waterstaat, 2020; Rijksoverheid, 2023; Rijkswaterstaat & Ministerie van Infrastructuur en Waterstaat, 2022), its implementation is hindered by fragmented logistics, linear procurement routines, and the absence of design-for-reuse protocols (Brinkhuijsen et al., 2020; Van Uden et al., 2025). Municipal infrastructure management continues to operate through siloed mandates and risk-averse decision-making (Said & Tempels, 2023), limiting the capacity to align maintenance, design, and demolition processes. For municipalities, strategies to advance paving material reuse must therefore be both systemic and spatially informed, integrating technical experimentation with institutional and territorial coordination.

Existing frameworks offer valuable but incomplete perspectives on how circularity could be spatially organised. The re-supply chain model (Van den Berghe & Verhagen, 2021) provides a useful lens for analysing material reproduction, but it primarily addresses contaminated building materials rather than the cleaner, modular flows typical of paving reuse. Similarly, territorialised circularity (Furlan et al., 2022) highlights where circular processes might occur but offers little guidance on the spatial requirements of reuse infrastructure. Research on Circular Building Hubs further advances understanding of spatial linkages between material sources and demand, yet most studies focus on construction waste at the building scale. Spatial parameters identified by Tsui et al. (2024) concern location suitability rather than facility size or operational requirements, while Van Uden et al. (2025) underline organisational and ownership complexities that may be less constraining for municipal-scale material reuse.

Altogether, this review identifies a distinct knowledge gap in understanding how the reuse of paving materials, and the infrastructure that supports it, can be operationalised within municipal practice in a spatially informed manner. While existing studies provide some indication of the scale of material flows, they offer little insight into the spatial demand generated by reuse infrastructure. Addressing these gaps is essential for developing practical, spatially grounded strategies that enable municipalities to integrate material reuse into routine infrastructure management.

Chapter 3

Methodology

This research builds on the knowledge gap identified in the previous chapter: the limited empirical understanding of how the reuse of secondary paving materials, and the infrastructure that supports it, can be operationalised within municipal practice in a spatially informed manner. Addressing this gap requires an approach that captures both the physical scale of material flows and the institutional conditions that shape them. This requires a mixed-method approach that combines quantitative analysis of material flows with qualitative insight into how municipal practices and reuse facilities shape their spatial and operational conditions.

3.1 Case Description

The research uses the Municipality of Rotterdam as a single case study. Rotterdam was selected because the study was conducted in collaboration with the municipality during the author's graduation internship. As the second largest municipality of the Netherlands, Rotterdam is analytically relevant due to its extensive road network, the implementation of a formal CE policy, and its data-driven approach to urban management. This combination makes Rotterdam a suitable and information-rich case for examining how paving material reuse can be operationalised within municipal road renovation practice. These factors provide both the institutional and empirical basis for the study: all quantitative datasets used originate from the municipality's internal systems, while the majority of qualitative data were also collected within the municipal organisation.

3.2 Research Design

This research applies an embedded mixed-methods design, as defined by Creswell and Plano Clark (2007). In this design, one data type provides a supportive, secondary role within a study primarily based on another data type. The embedded data can be collected before, during, or after the implementation of the larger design, depending on the purpose of the embedded component. This approach is advantageous because one method requires less data than the other, making it suitable for graduate-level research.

In this research, quantitative analysis, specifically a Material Flow Analysis (MFA), forms the methodological core. According to Xavier et al. (2023), MFA is a mass-balance-based tool that systematically traces inputs, processing, and outputs within a defined system boundary. All materials released remain accounted for within the system. Within this research the MFA is chosen to quantify paving material flows linked to road renovation, and to calculate of which circular flows they consist: they are either reused, stored, or diverted to downcycling pathways.

The qualitative components are embedded at two points in the research process to inform and interpret the quantitative results. First, findings from policy documents and expert interviews are used to define the scope and system boundaries of the MFA. Second, findings from site visits to reuse facilities, supplemented by desk research, are used to estimate the spatial demand associated with the calculated material flows. Together, these steps establish a quantitative baseline of circular paving material flows and the resulting spatial requirements for storage and processing.

Finally, this provides the basis for identifying realistic adjustment pathways derived from qualitative insights and for evaluating their potential impacts using quantitative results. These three stages of the research process are illustrated in Figure 3.1.

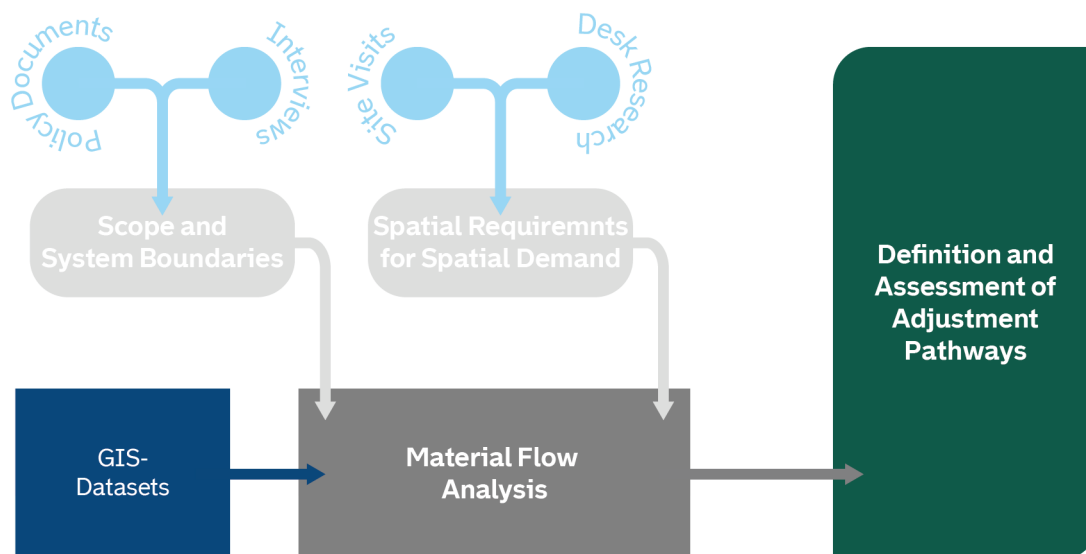


Figure 3.1 Research design and methodological sequence. Adapted from Creswell and Plano Clark (2007).

3.3 Data Collection

In line with the quantitatively driven embedded mixed-methods design described in the previous section, the data collection strategy combines quantitative and qualitative inputs within one coherent framework. Accordingly, the section is divided into two parts: quantitative data collection and qualitative data collection.

3.3.1 Quantitative Data

The approach for quantitative data collection was informed by existing MFA methods, most notably the study by Van den Berghe & Verhagen (2021), which analysed the metabolic reproductive system of concrete within the built environment of The Hague. In their research, spatial data on the existing building stock were combined with the municipality's construction and demolition agenda to determine annual inflows (new construction) and outflows (demolition) between 2020 and 2025. This approach demonstrates that understanding circular material systems requires data on three key components: the existing stock, the new demand, and the temporal dynamics of these flows, referring to when and where materials are released within the system over time.

Translated to the context of secondary paving materials, this means that datasets are required to represent (1) what currently exists in the urban road network, (2) what will be needed for upcoming projects, and (3) how these stocks and demands evolve over time. Through discussions within the municipality, three relevant spatial datasets were identified that form the empirical foundation for quantifying secondary paving material flows and assessing the spatial demand for reuse infrastructure over time:

- **Wegvakonderdelen** (Road Segments): A vector dataset categorising all road segments within Rotterdam, including attributes such as paving type, surface area, and function (roadway, bicycle path, sidewalk).
- **Klinkerkaart Rotterdamse Stijl** (Rotterdam Style Paving Block Map): A vector dataset indicating the preferred paving material after maintenance, as specified in the Rotterdam Style Guide.
- **Projecten in de Gebieden** (Planned Renovation Projects): A vector dataset of scheduled maintenance works (2025–2038), spatially defined from neighbourhood to street-segment scale, including attributes for planned start and end year as well as the reason for renovation.

3.3.2 Qualitative Data

Qualitative data that was collected for this research concerned four types of sources. These four types of sources are Policy Documents, Expert Interviews, Site Visits, and Desk Research. Policy Documents and Expert Interviews provided the basis for answering sub question 1, while the site visits and desk research provided insights for answering sub question 2.

Policy Documents

The policy documents reviewed in this study were selected for their relevance to the municipality's vision and operationalisation of circularity, the design of public space, and the management of road infrastructure. Documents were identified either through systematic searches in the municipality's internal online environment or were suggested during expert interviews. Together, they define the formal framework that governs Rotterdam's rules, standards, and ambitions for circular construction, paving material selection, planning cycles, and material reuse. The reviewed documents include:

- **Rotterdam Circulair Programma 2023–2026** (Programme Circular Rotterdam 2023–2026)
- **Handboek Rotterdamse Stijl** (Rotterdam Public Space Style Guide)
 - **Toolkit Rotterdamse Stijl** (Rotterdam Public Space Style Toolkit)
- **Strategisch Assetmanagementplan** (Strategic Asset Management Plan)
 - **Assetmanagementplan Wegen** (Asset Management Plan Roads)
- **Afwegingskader Hergebruik Materialen Buitenruimte** (Assessment Framework for Reuse of Materials in Public Space)

3 Methodology

Semi-Structured Interviews

To complement these documents, semi-structured expert interviews were conducted to capture how these policies and guidelines are applied in practice. This method is well suited for obtaining professional perspectives on focused topics (Hammarberg et al., 2016). Interviewees were selected through purposeful sampling, which involves identifying individuals who possess specialised knowledge or experience related to the phenomenon of interest (Palinkas et al., 2015). The selection targeted individuals with specialised knowledge of circular material use in road infrastructure and aimed to represent diverse professional roles in procurement, asset management, engineering, and design.

A total of five interviews were held with officials from the municipal clusters City Management and Urban Development, an overview can be seen in Table 3.1. A tailored interview guide, which can be found in Appendix B, was developed to structure the conversations. It included questions about each participant's professional role, project experience, interdepartmental collaboration, and perceived opportunities and barriers to circular material reuse. Each interview concluded with an open reflection, allowing respondents to share additional insights.

Table 3.1 Overview of interviewees.

Interviewee	Role	Cluster	Length
Interviewee 1	Asset manager roads	City management	42 minutes
Interviewee 2	Advisor public procurement	City management	45 minutes
Interviewee 3	Advisor circularity	City management	47 minutes
Interviewee 4	Road engineer	Urban development	52 minutes
Interviewee 5	Senior landscape designer	Urban development	68 minutes

Site visits

Given that municipal reuse infrastructure is a recent and highly specific field, limited formal data exist on its spatial organisation and daily functioning. Therefore, site visits were carried out to gain first-hand insights into the operational and spatial characteristics of such facilities. As explained by Tabačková (2024), site visits enable direct physical analysis of a place through embodied observation, which helps capture missing or outdated information that cannot be obtained through maps or documents alone. Rather than taking an open exploratory approach, which is guided by encounters and curiosity, each visit was structured around a predefined set of guiding questions, which can be found in Appendix C, that were addressed organically. Two municipalities were visited, both operating dedicated reuse facilities, an overview can be seen in Table 3.2. Observations were documented through field notes and photographs focusing on spatial layout, operational routines, and contextual characteristics.

Table 3.2 Overview of site visits.

Municipality	Guide	Name of site
Apeldoorn	Circularity advisor and terrain manager	Material storage terrain
Haarlem	Circularity advisor	Circular material hub

Desk Research

Building on the observations and insights from the site visits, desk research was conducted to identify professional and technical references that further substantiate the spatial characteristics observed in practice. This review focused on various forms of reuse infrastructure and examined how existing literature and professional sources describe aspects such as storage logistics, operational organisation, and potential multifunctionality of reuse hubs. The purpose of this review was to translate the qualitative impressions gathered on-site into a more systematic understanding of the spatial requirements associated with circular material reuse.

3.4 Data Processing and Analysis

Similar to the division of section 3.3, this section is also divided between quantitative and qualitative data. While data processing refers to the preparation and structuring of quantitative datasets, data analysis involves the interpretation of qualitative material to identify thematic patterns and practical insights.

3.4.1 Quantitative Data

The spatial datasets mentioned in Section 3.3.1 were integrated in QGIS through two spatial joins. First, attributes from the Road Segments dataset were matched with their designated post-maintenance material type from the Rotterdam Style Paving Block Map. Second, the resulting dataset was intersected with the Planned Renovation Projects dataset, retaining only segments scheduled for renovation.

The resulting dataset contained road segments scheduled for renovation, their current paving material, construction date, and function, as well as the intended post-renovation material. The data were then exported to Excel for cleaning. Irrelevant columns and rows were removed, including projects already completed (end date before 2025). Road segments were grouped per maintenance project, and for each project the total surface area per paving type was aggregated.

This process produced a structured overview of planned road renovation projects, including the reason for renovation, start and end year, and the associated stock and demand of paving materials in square metres. The resulting dataset thus captures both the current condition of paving materials (stock) and the projected demand (new materials) required for future projects. This forms the basis of calculating the reusable amount of each paving material, and the resulting storage demand.

3.4.2 Qualitative Data

The qualitative data analysis followed two stages corresponding to the two embedding points described in Section 3.2.

Analysis of Scope and System Boundaries

A thematic analysis was conducted based on the policy document review and the semi-structured expert interviews. Rather than applying formal coding techniques, the material was analysed inductively through iterative reading and comparison to identify recurring patterns, tensions, and alignments between policy ambitions and implementation practices. The analysis focused on how circularity is interpreted and operationalised within the municipality. This process led to the identification of three analytical themes that structure the findings:

1. Overarching Positioning of Circularity in Municipal Policy
2. Road Maintenance Planning
3. Road Maintenance Design

These themes provide a framework for understanding both the formal structure and the practical execution of reuse efforts in Rotterdam's public space management. They also defined the boundaries and assumptions applied in the MFA.

Analysis of Spatial Requirements for Spatial Demand

The data gathered from the site visits and desk research were analysed together to contextualise the spatial dimension of reuse. Based on observations from the site visits, key similarities and differences between the two facilities were identified and supplemented by desk research to establish clear definitions of different types of reuse infrastructure applicable to the Rotterdam case.

Subsequently, the observations were filtered to those directly related to the storage and processing of secondary paving materials, as well as the minimal additional functionalities required

for such facilities. This filtering distinguished between aspects common to both sites and those specific to each case. The grouped observations then formed the empirical basis for defining spatial requirements. Desk research was used to supplement these categories with technical reference data necessary to calculate the net floor area corresponding to the projected storage demand.

3.5 Ethical Considerations and Limitations

Ethical considerations in this research primarily concerned the handling of data gathered from internal municipal representatives and external stakeholders. Interviews with internal municipal officials were conducted without formal consent forms, as participants acted in their professional capacity within the organisation. However, all participants were informed about the research objectives and data handling procedures in advance, and recordings were made only with verbal consent. For external representatives involved in the site visits, formal consent forms were signed prior to each visit to ensure informed participation and agreement on the academic use of collected information (see Appendix D). All respondents were anonymised in transcripts and summaries, and the summaries of findings were shared with both interviewees and site visit participants to verify factual accuracy and confirm the validity of interpretations..

The interview data are limited to five municipal officials; perspectives from contractors, suppliers, or residents were not included, which limits representativeness. The two site visits, conducted in Apeldoorn and Haarlem, provided valuable insights into the spatial and operational characteristics of reuse infrastructure but represent snapshots of local practice that may not be fully generalisable to Rotterdam. Several other circular hub locations were contacted during the exploratory phase, yet due to limited staff availability and time constraints, most could not accommodate a visit. The small number of such facilities in the Netherlands further constrained the empirical scope.

The translation of qualitative findings into quantitative assumptions introduces an element of subjectivity, particularly regarding reuse rates, storage durations, and allocation rules. While these estimates were grounded in expert judgement and cross-checked with available data, they remain interpretative. Nevertheless, combining multiple qualitative and quantitative sources provides a contextually robust foundation for understanding current practice

3.6 Documentation of the Results

The presentation of results, outlined in the following three chapters, follows the structure of the mixed-methods framework described in this chapter:

- **Chapter 4** presents a detailed overview of Rotterdam's current road renovation practices and ambitions for paving material reuse, and translates these practices into circular material flows.
- **Chapter 5** builds on this by linking the identified flows to the resulting spatial demand for reuse infrastructure, by defining the spatial requirements of two distinct reuse facility types.
- **Chapter 6** integrates and interprets the findings by outlining potential adjustment pathways and quantifying their associated benefits.

Chapter 4

Paving Material Reuse in Rotterdam

This chapter analyses how circularity in road renovation is organised in Rotterdam and how this shapes paving material flows. It first outlines the municipality's ambitions for reuse, focusing on how material selection and maintenance planning are embedded in policy frameworks and operational practices. It then quantifies current paving material flows by calculating the inflows and outflows from planned renovation projects and assessing the technically reusable share. These flows are evaluated in terms of their potential to reduce virgin material demand, CO₂ emissions, and costs. Together, these findings establish a baseline for examining spatial requirements and testing optimisation strategies in the following chapters.

4.1 Rotterdam's Current Paving Material Reuse Strategy and Ambitions

This section analyses Rotterdam's current road maintenance strategy and ambitions for paving material reuse by combining municipal policy frameworks with practitioner interviews. Together, these sources show how reuse ambitions are both formalised in policy and interpreted in day-to-day practice. Detailed summaries of the reviewed policy documents and interviews are provided in Appendix D and Appendix E, respectively.

Rotterdam has committed to national and European circularity targets, aiming to halve the use of primary raw materials by 2030 and to achieve full circularity by 2050. These ambitions are formalised in the *Rotterdam Circular 2023–2026 Programme*, which builds on the R-ladder, practice-based experimentation, and value chain collaboration. Construction is identified as a priority sector because of its scale and potential impact. As owner of public space, commissioning authority for redevelopment, and purchaser of materials, the municipality plays a pivo-

4 Paving Material Reuse in Rotterdam

tal role in shaping material reuse practices (Gemeente Rotterdam, 2023). Achieving the 2030 target would require roughly half of all streets to be reconstructed with reused materials, while current practice amounts to only about 5%. Moreover, redevelopment or elevation projects typically require a 20% inlay of new material, further complicating this ambition (Interviewee 5).

Paving materials have a particularly central role in this transition. Annual procurement of 60–70 million kilograms of concrete products, mainly paving stones and tiles, accounts for about 70% of CO₂ emissions from public space works (Interviewee 3). To address this, Rotterdam has set the goal of opening at least one circular material hub by 2026 (Gemeente Rotterdam, 2023). Currently, two sites have been opened that approximate this goal: Bunschotenweg in Heijplaat (ca. 1 ha, of which 700 m² is paved for storage) and a smaller facility in Reyeroord (Interviewees 1, 2, and 3). Both sites, however, can be considered temporary stopgaps and remain limited in scale and capacity (Interviewee 5). Further development at Bunschotenweg is constrained by costs and land-use agreements (Interviewees 2 and 3), while the Reyeroord site mainly serves local projects and cannot absorb city-wide flows (Interviewees 1 and 4). The current depots therefore illustrate the broader tension in Rotterdam's circular transition, where formal reuse ambitions encounter structural barriers such as limited depot capacity, and fragmented responsibilities. The current depots therefore illustrate the broader tension in Rotterdam's circular transition, where formal reuse ambitions encounter structural barriers such as limited depot capacity and fragmented responsibilities. Furthermore, while physical space is available, it is rarely reserved for circular hubs; other priorities almost always take precedence (Interviewee 5).

Current ambitions for reuse are further shaped by the standards that steer material selection in the design of roads and by the way renovation projects are planned and executed. Together, these factors shape the extent to which paving materials can be reintegrated into municipal projects and highlight the structural challenges that remain.

4.1.1 Road Maintenance Design

The Rotterdam Public Space Style Guide and its accompanying Toolkit provide the framework for the design of the city's public space, including roads. Circularity is one of seven core values and is embedded through the principle of "circular, unless", making reuse the default unless deviations are justified on technical, functional, or aesthetic grounds. Material choices are highly standardised, limited to concrete bricks, fired clay pavers, tiles, natural stone, and asphalt, selected for aesthetics, durability, and environmental performance (Gemeente Rotterdam, 2024a, 2024b). Table 4.1 illustrates the environmental and economic impacts of newly produced modular paving materials, highlighting their significant resource intensity.

Table 4.1 The environmental and economic impact of newly produced paving materials (Gemeente Rotterdam, 2024a).

Product	Raw materials per m ²	CO ₂ emissions per m ²	Cost per m ²
Concrete paving blocks	176 kg	19 kg	€18.50
Brick paving blocks	168 kg	14 kg	€29.50

While standardisation supports visual coherence and logistical efficiency, it constrains innovation. Many circular alternatives, such as products derived from dredged harbour sludge, do not meet existing specifications in size, colour, or structural performance. Only fully compatible innovations can be integrated without additional sorting or adjustment, reinforcing a preference for uniformity to keep reuse scalable and manageable. Moreover, increasing the number of different materials in the streetscape complicates maintenance and may result in such a poor overall appearance that premature replacement becomes unavoidable (Interviewees 1 and 5).

The Paving Block Map within the Style Guide, shown in Figure 4.1, specifies which type of modular paving material is prescribed at which location within the city, ensuring consistency in the streetscape. It distinguishes between the materials from the toolbox: three types of concrete paving blocks, standard grey (BSS-RS GR), a specific type for the Nesseland district (BSS-RS NE), and clay brick-look concrete (BSS-RS WB), alongside brick paving blocks (SBS-RS) (Gemeente Rotterdam, 2024b). Deviations from the paving block map must be reviewed by the Public Space Advisory Committee, with most requests concerning alternative materials or expressive design features. Figure 4.1 shows a clear preference for fired clay bricks over concrete paving blocks, as bricks are considered to weather more attractively in public space (Interviewee 5).

The map has recently been updated to also indicate designated areas where older, non-standard concrete paving blocks (predating the 1996 introduction of standardised procurement) can be reused (Gemeente Rotterdam, 2024a). These blocks are more difficult to apply because they deviate in colour from standardised ones, for instance, purple or black. It has therefore been decided that such blocks may be reused in colour-mixed applications (BSS non-RS) in specified areas. These locations were selected because their high proportion of greenery makes visual variations less noticeable. This patchwork reuse of older concrete blocks is regarded as a temporary solution, since the ultimate goal of the Rotterdam Style Handbook and its accompanying toolbox is to achieve uniformity across the city's streetscape (Interviewees 1 and 5).

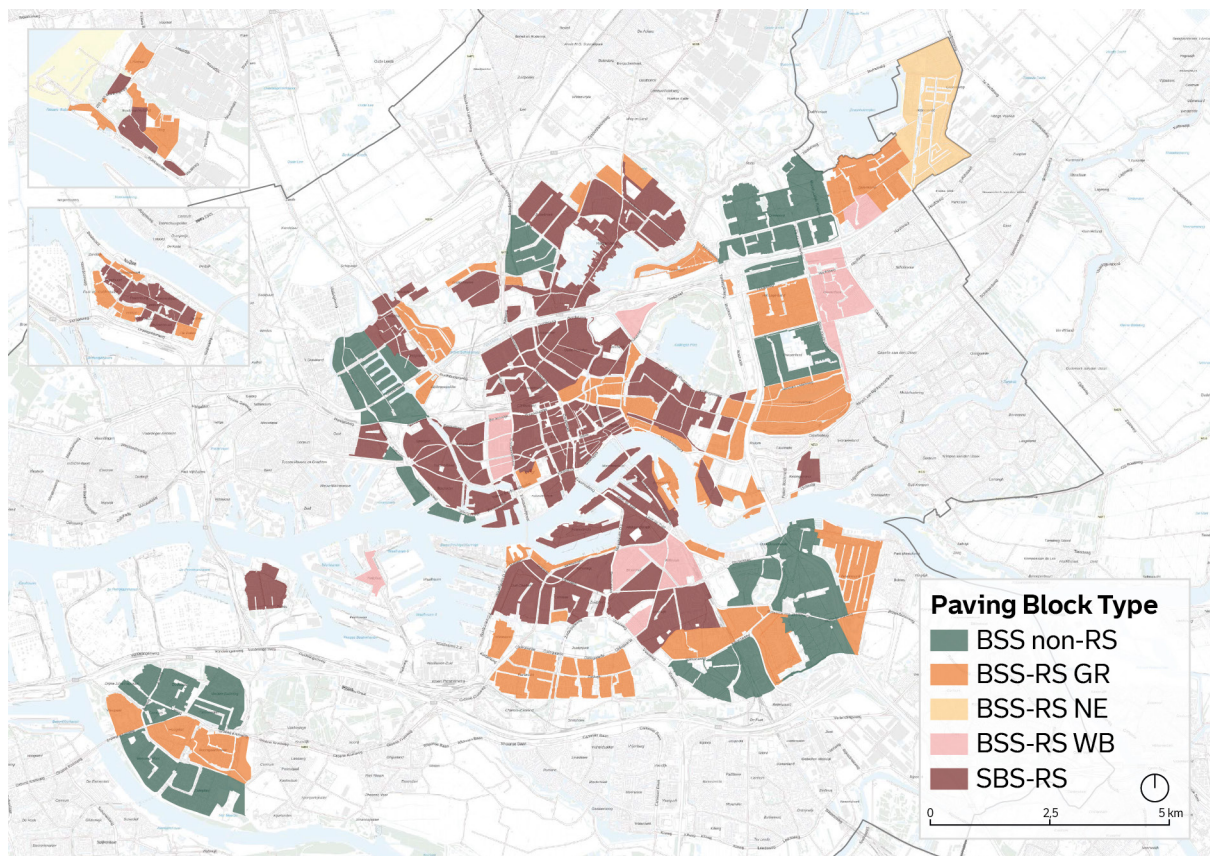


Figure 4.1 The Rotterdam Public Space Style Guide Paving Block Map.

4.1.2 Road Maintenance Planning

Since 2019, Rotterdam has managed public space through a programmatic, risk-based approach formalised in the Strategic Asset Management Plan. Public space is framed as a socially valuable system, with circularity, climate adaptation, and the energy transition integrated as core assessment criteria (Gemeente Rotterdam, 2019b). The Asset Management Plan for Roads operationalises these principles, covering a network in which 75% of paved surfaces consist of modular elements (brick and concrete paving stones and tiles) and 25% of asphalt or poured concrete (Gemeente Rotterdam, 2019a).

Following the methodology of the Centre for Regulation and Research in Civil Engineering, Hydraulic Engineering, Road Construction and Traffic Engineering (CROW), four intervention types are distinguished: periodic maintenance, corrective repair, major maintenance, and replacement. Lifespans are estimated at 45 years for asphalt and 60 years for modular paving, supported by inspection and predictive data (Gemeente Rotterdam, 2019a). In practice, widespread subsidence shortens depreciation cycles to 20, 40, and 60 years. Sewer deterioration is the primary trigger for street redesign, with around 80% of roadworks aligned to sewer replacement cycles and executed as integrated projects that also renew above-ground elements (Interviewee 1). Planned maintenance projects are continuously mapped, from neighbourhood-wide interventions to single street segments, and linked to start and end years between 2025 and 2038. The spatial distribution of these projects is shown in Figure 4.2.

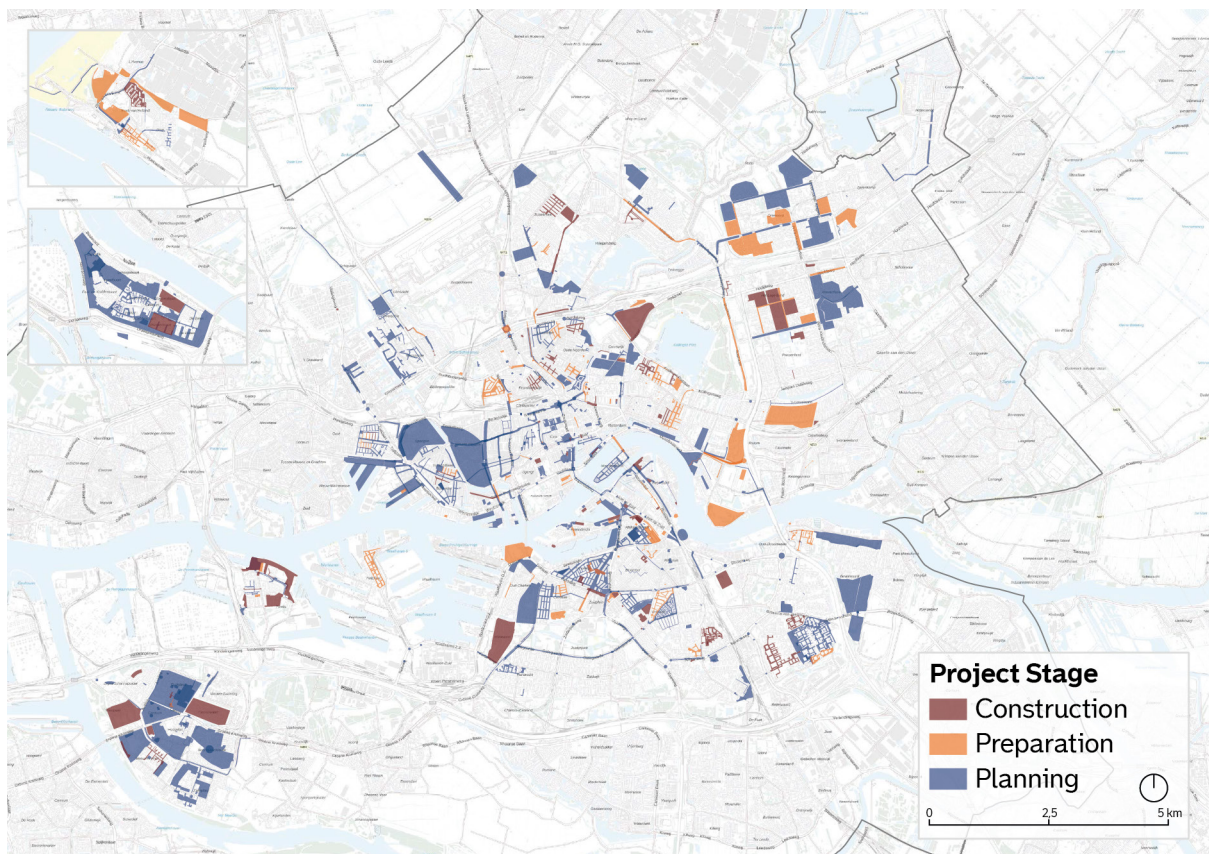


Figure 4.2 Spatial distribution of planned renovation projects in Rotterdam.

These renovation cycles determine when paving materials are released, creating opportunities for reuse. However, the fate of recovered materials depends strongly on the type. Asphalt recycling is well established through regional plants, producing up to 65% recycled content in sub-layers and 30% in top layers (Interviewee 4). In contrast, modular paving blocks, though often technically suitable for reuse, are still frequently replaced and diverted to contracted rubble processors for downcycling (Interviewees 4 and 5). To counter this, the 2024 Assessment Framework for Reuse of Materials in Public Space introduced standardised inspection criteria, focusing on damage, shape, and surface quality, to guide asset managers in determining which materials qualify for reuse (Gemeente Rotterdam, 2024a). Table 4.2 summarises the environmental and economic benefits of reusing paving materials compared to new production.

Table 4.2 The environmental and economic impact of reused paving materials (Gemeente Rotterdam, 2024a).

Product	Raw materials per m ²	CO ₂ emissions per m ²	Cost per m ²
Concrete paving blocks	0 kg	0 kg	€9.20
Brick paving blocks	0 kg	0 kg	€9.20

In practice, recovery rates vary. Roadway paving blocks and bricks are typically cleaner and better maintained than pedestrian surfaces, resulting in higher reuse yields. Recently, the municipality has started to require that materials passing inspection be cleaned, sorted, and palletised directly on project sites. The ambition is to store these packaged elements in the municipal inventory, creating a closed supply for future projects (Interviewees 2 and 3). Whether this is already happening on a large scale remains unclear (Interviewee 5).

4.2 Calculating Circular Paving Material Flows

Building on the design standards and maintenance planning outlined in the previous section, this chapter quantifies the actual flows of paving materials under current municipal practices. It provides a baseline for subsequent spatial and optimisation analyses. The focus is on gross material flows: how much surface area of each paving type will be released and how much will be required, derived from municipal datasets and processed through a spatial analysis workflow. These results form the foundation for the following section, which assesses the technically reusable fractions of these flows.

The scope of the analysis is defined by the design and planning framework described in Section 4.1. Specifically, it focuses on roadway surfaces paved with the five types of modular paving blocks included in the municipal standards, as well as asphalt roadways that are planned to be substituted with modular paving blocks. Roadway materials are prioritised because they are generally cleaner and better maintained than pedestrian surfaces and are therefore expected to have a higher potential to meet the aesthetic and technical requirements for reuse.

4.2.1 Total Stock and Demand of Paving Materials

Based on the processed municipal datasets described in the previous chapter, this section presents the first quantitative results of the analysis. It provides an overview of material outflows (current stock) and inflows (future demand) linked to planned renovation projects for five paving material groups: (1) standardised brick paving blocks (SBS), (2) grey standardised concrete paving blocks (BSS-RS GR), (3) warm brown standardised concrete paving blocks (BSS-RS WB), (4) non-standard concrete paving blocks from pre-1996 inventories (BSS non-RS), and (5) asphalt.

A limitation in the data is that all older, non-standard concrete paving blocks predating the 1996 introduction of standardised materials were recorded as a single material category (BSS non-RS). In reality, these blocks vary in colour and finish. To reflect this, the stock of older blocks was subdivided into six storage groups based on construction year, to simulate colour varia-

4 Paving Material Reuse in Rotterdam

tion. This distinction was not required on the demand side, as these blocks are intended for mixed “patchwork” applications.

The relative sizes of these flows are shown in Figure 4.3, with the full overview of material inflows and outflows provided in Appendix F. If all calculated demand were to be met with newly produced materials, where the demand for older non-standard blocks is replaced by newly produced concrete paving blocks, total consumption between 2025 and 2038 would amount to 360.0 kilotons of raw material, 34.8 kilotons of CO₂ emissions, and €49.5 million in costs. These calculations are based on the environmental and economic values of new paving materials shown in Table 4.1. This “worst-case” scenario underlines the potential climate and cost benefits of substituting recovered materials for new production.

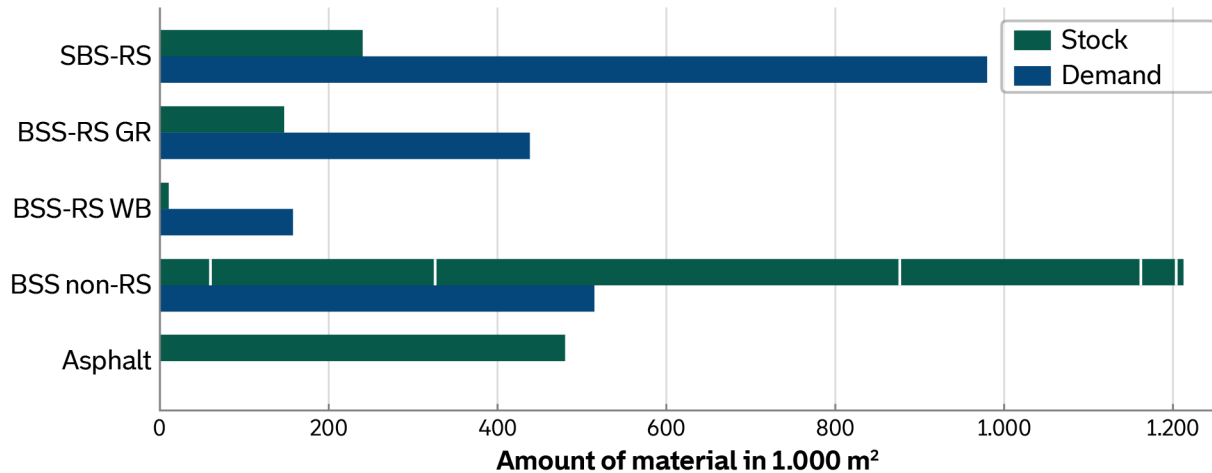


Figure 4.3 Total stock and demand of paving materials from planned road renovations.

4.2.2 Technically Reusable Share of Paving Material Flows

When translating the material flows from the previous section into circular material flows, they can be divided into three streams. The first is the technically reusable share of the stock, which needs to be stored for secondary use. This share is calculated using reuse rates, and for this thesis two levels of recovery are considered: theoretical reuse rates, representing the maximum technically achievable recovery, and realistic reuse rates, reflecting observed practice in municipal projects. The second stream is the remaining flow from the stock, consisting of elements broken due to age or dismantling, which cannot technically be reused in visible applications. Instead, this fraction is considered inboud: material that is sent directly to the crusher and thereby downcycled into lower-grade applications (e.g. road base or aggregate). The third stream is the demand for new materials, which is equal to the total projected demand minus the reusable share.

To determine the theoretical reuse rates, the technical lifespan forms the basis. For brick paving blocks (SBS), a functional lifespan of 130-140 years is assumed, based on Nusselder et al. (2020). Taking into account the average technical lifespan of roads (40 years), bricks with a construction date up to 100 years ago are considered suitable for reuse. For standardised concrete paving blocks (BSS-RS GR and BSS-RS WB), lifetime-based dropout rates are derived from the extended lifespan scenario by (Keijzer et al. (2015): 10% of elements reach end-of-life after 25 years, 30% after 50 years (cumulative), and all remaining after 75 years. For non-standard concrete paving blocks (BSS non-RS), installed prior to the 1996 introduction of the Rotterdam Public Space Style Guide, it is assumed that 20% of the stock consists of thinner types that are structurally unsuitable for reuse and are therefore excluded. The remaining 80% follow the same degradation intervals as BSS-RS.

For the realistic reuse rates, observed practice in municipal projects suggests additional reductions. For most materials, the overall reuse potential is adjusted downward using a 0.85 factor

(equivalent to a 32% breakage rate instead of 20%). For SBS, a higher breakage rate is assumed because they are typically less tightly laid and more prone to cracking due to vibrations during use and dismantling. To reflect this, their realistic reuse rate is reduced further.

These two levels should not be understood as separate scenarios but as a range, indicating the lower and upper boundaries of what can be achieved in practice. Table 4.3 summarises the net reuse rates per material type under both realistic and theoretical assumptions.

Table 4.3 Net reuse rates by material type.

Age	Realistic reuse rates					Theoretic reuse rates				
	0-24	25-49	50-74	75-100	≥ 101	0-24	25-49	50-74	75-100	≥ 101
SBS-RS	68%	55%	40%	0%	0%	80%	80%	80%	80%	0%
BSS-RS GR	68%	61.2%	47.6%	0%	0%	80%	72%	56%	0%	0%
BSS-RS WB	68%	61.2%	47.6%	0%	0%	80%	72%	56%	0%	0%
BSS non-RS	54.4%	49.0%	38.1%	0%	0%	64%	57.6%	44.8%	0%	0%

Applying these reuse rates to the material flows yields recoverable shares of 36.4% under realistic assumptions and 39.8% under theoretical assumptions. The resulting shares are illustrated in Figures 4.4 and 4.5, with the underlying data for these figures provided in Appendix G.

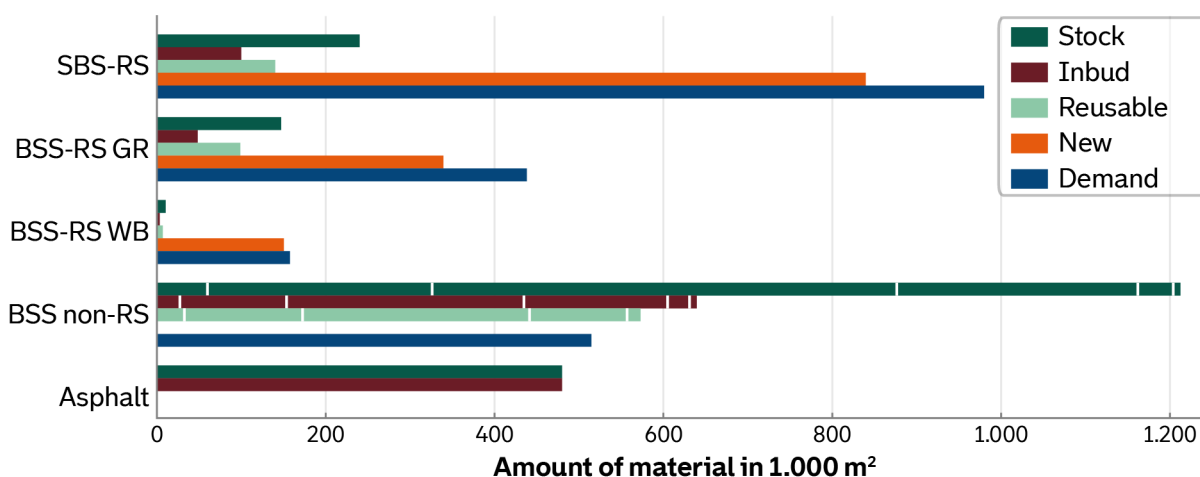


Figure 4.4 Share of reusable paving materials under realistic assumptions.

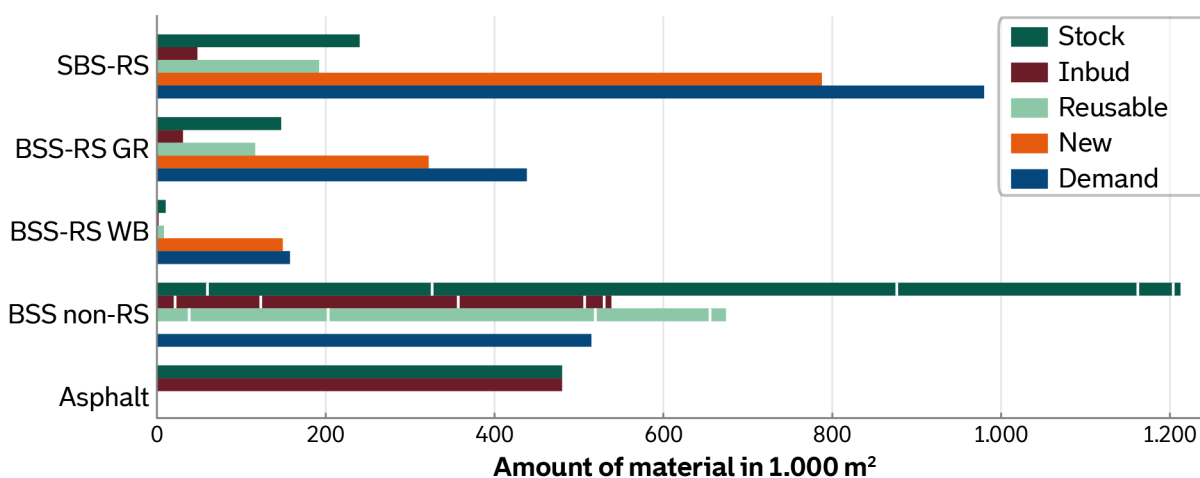


Figure 4.5 Share of reusable paving materials under theoretic assumptions.

Based on the values from Table 4.2, The Environmental and Economic Impact of Reused Paving Materials, the new environmental impact can be calculated. At the lower end of the range, technically reusable paving materials account for about 36.4% of total demand. This would reduce

4 Paving Material Reuse in Rotterdam

virgin material consumption to 227.3 kilotons, CO₂ emissions to 18.6 kilotons, and total costs to €40.8 million. At the upper end of the range, technically reusable paving materials account for 39.8% of total demand. This would reduce virgin material consumption to 215.2 kilotons, CO₂ emissions to 17.6 kilotons, and total costs to €39.6 million.

4.3 Conclusion

The analysis demonstrates that the technically reusable fractions of standardized materials (SBS, BSS-RS GR, and BSS-RS WB) all fall within their projected demand, meaning that under current planning cycles these categories can, in principle, be fully reintegrated into municipal projects. By contrast, the amount of technically reusable surface of non-standard pre-1996 paving blocks (BSS non-RS) consistently exceeds demand, resulting in structural surpluses between 58,327 - 159,390 m². Consequently, only 84 - 93% of the total reusable material can actually be reused. At the same time, BSS-RS GR shows differences in technically reusable supply and demand between 339,321 - 321,830 m². This indicates that, in technical terms, part of the surplus of BSS non-RS could offset the shortage of BSS-RS GR if substitutions were allowed. However, this potential remains restricted by the design constraints of the Rotterdam Style Guide, which limit the application of non-standard materials across the city. These balances are summarised in Table 4.4.

Table 4.4 Balance between technically reusable materials and demand.

Material	Reusable (m ²)	Demand (m ²)	Balance (%)
SBS-RS	142,016 - 192,123	979,789	14.3 - 19.6
BSS-RS GR	98,892 - 116,383	438,213	22.6 - 26.6
BSS-RS WB	7,080 - 8,343	15,572	4.5 - 5.3
BSS non-RS	572,963 - 674,025	514,636	111.3 - 131.0

From a climate and cost perspective, both scenarios underline the significant benefits of reuse. Avoiding new production could reduce virgin material use by 36.9- 40.2%, CO₂ emissions by 46.5 - 49.4%, and lower costs by 17.4 - 19.9% compared to the worst-case of full replacement with virgin materials. The detailed results are presented in Table 4.5.

Table 4.5 Overview of material impact reductions through reuse of paving materials.

Scenario	Reusable (m ²)	Demand (m ²)	Balance (%)
Worst-case	360.0	34.8	49.5
Current reuse ambitions	215.2 - 227.3	17.6 - 18.6	39.6 - 40.8

Overall, the findings highlight that Rotterdam's ambitions concerning the reuse of modular paving materials already deliver substantial impact reductions. While the ambition of achieving uniformity in paving materials is, in principle, beneficial for future circularity, the structural oversupply of non-standard paving blocks shows that current policy frameworks do not yet provide sufficient flexibility to accommodate what is technically available for reuse today. This underlines the need for alternative allocation strategies.

Chapter 5

The Spatial Demand of Reuse

This chapter translates the paving material flows established in the previous chapter into spatial demand for reuse infrastructure. It first introduces the role of hubs in construction logistics and processing, drawing on operational examples. From these cases, key spatial requirements for storage, logistics, and supporting functions are derived, alongside criteria for site selection. These requirements are then applied to Rotterdam's material flows to calculate net floor areas needed for these facilities.

5.1 Circular Material Hubs

Facilitating modular paving material reuse requires more than technical adaptation; it calls for resource sheds, which are conceptualized as operational sites where secondary materials are stored, processed, and redistributed as new inputs (Furlan et al., 2022). Resource sheds are not new innovations but differ per sector. In the construction sector, resource sheds take the form of circular material hubs (Metabolic et al., 2022).

Circular material hubs are not completely innovative; they build on the more conventional logistical construction hubs originally developed as an alternative to the traditional construction supply chain. Traditionally, contractors or subcontractors place orders directly with suppliers, who then deliver materials straight to the construction site. Logistical Construction Hubs are facilities to route through deliveries from multiple suppliers, here goods are consolidated, inspected, and temporarily stored before being bundled and sent to the site. While such hubs reduce transport movements, lower congestion, and improve air quality in cities and regions, they are not inherently aimed at enabling circularity in the construction sector, as they primarily focus on the distribution of new building components (De Bes et al., 2018; Metabolic et al., 2022).

5 The Spatial Demand of Reuse

Circular material hubs differ from logistical construction hubs through their focus on the recovery, temporary storage, and redistribution of building components from existing stock. Metabolic et al. (2022) further distinguish two types: storage hubs for secondary materials and circular construction hubs, with key differences in function. The following section describes the definitions of these types, explains how they differ, and presents operational examples of both hub types in Dutch infrastructure practice, which were visited. More detailed descriptions of these site visits can be found in Appendix H.

5.1.1 The Storage Hub

The Storage Hub is meant for the temporary storage of materials from demolition or maintenance projects when direct reuse is not feasible due to mismatched planning or location (Metabolic et al., 2022). As such, it is very similar to the logistical construction hub, but differs from it as it focuses on secondary materials rather than new materials. An example is located in Apeldoorn, on the Laan van de Zodiak, which covers approximately 3,000 m² and is owned and managed by the municipality. Over the past five years, the hub has been situated in a new residential neighbourhood that was in full construction, but this area is now largely completed. As a result, the facility will soon be relocated to another site within the municipality. Plans for the new location are underway to expand the hub with a dedicated 4,000 m² circular materials zone, physically separated from the regular municipal depot.



Figure 5.1 Storage Hub in Apeldoorn (own image).

The current hub stores paving stones, curbstones, and street furniture. Materials arrive already palletised by contractors, and are sorted by type and stacked on location. There is no on-site processing due to noise concerns for the surrounding neighbourhood. The site frequently reaches capacity due to the irregular shape and size and the low stacking potential of some of the items accepted (see Figure 5.1). Coordination is minimal: deliveries are often unannounced and inventory management is reactive. Although the municipality uses DuSpot as a digital tool for material matching, most reuse still depends on informal communication and individual initiative. Despite promising small-scale applications, the lack of policy frameworks within the municipality, such as a handbook for the design of public space, leads to a higher diversity of materials used in public space and limits broader integration of circularity.

5.1.2 The Circular Construction Hub

The Circular Construction Hub serves as collection, processing, and distribution point for recovered construction materials, including opportunities for upcycling and added functions such as education, social employment, or logistics services (Metabolic et al., 2022). These hubs go beyond temporary storage by actively reconditioning materials for reuse. An example is located in Haarlem, on a former demolition site in the Waarderpolder industrial zone. The site, which spans 7,200 m², is jointly owned by three contractors, who are responsible for the municipalities public space maintenance projects, through an eight-year framework agreement with the municipality and is managed by a fourth logistical party.

At the hub, which offers space for approximately 10,000 m² of paving elements, materials are received in bulk (see Figure 5.2), unloaded on-site, and then cleaned with high-pressure air or water. Materials are sorted by type and mechanically stacked on pallets labelled for reuse. Items without immediate reuse potential are either distributed via DuSpot or reassigned through contractor networks. The site integrates electronic vehicle charging and other logistical services, while timber from municipal tree maintenance is dried and sawn on-site, adding an upcycling dimension and enhancing its multifunctionality.



Figure 5.2 Circular Construction Hub in Haarlem (own image).

5.2 Spatial Requirements for Calculating Spatial Demand

The typologies and cases introduced in Section 5.1 can be directly linked to Rotterdam's current reuse practices. For standardised paving materials (SBS, BSS-RS GR, and BSS-RS WB), which conform to the Rotterdam Public Space Style Guide and are already cleaned, sorted, palletised, and wrapped at the construction site, the storage hub configuration is most relevant. In contrast, for non-standardised paving materials (BSS-non-RS) that deviate in size, colour, or finish, the circular construction hub is required. These materials need additional handling before reuse, such as mixing colour batches or mechanical palletising, to make them suitable for visible applications.

However, while Section 5.1 provides a good understanding of the facilities needed for effective paving material reuse, it does not yet allow the calculation of spatial demand for such facilities. Based on the site visits in Apeldoorn and Haarlem, four types of spatial requirements were defined for the storage and processing of paving materials, derived from the observed site layouts and operations:

- **Requirements related to on-site material storage**, covering how much paving material can fit on a pallet, how high it can be stacked, and the projected floor area per pallet.
- **Requirements related to on-site logistics**, defining the internal circulation space required for the movement of equipment and personnel, as well as the loading areas and the space needed for mechanical palletising and material handling.
- **Requirements for additional on-site functions**, including facilities that support daily operations such as office space and parking.
- **Requirements related to site selection**, concerning the external spatial context and the types of locations suitable for such hubs.

These observations were further specified through desk research into quantifiable requirements that allow for calculating net floor area; the detailed descriptions and calculations are provided in Appendix I.

Table 5.1 synthesises these spatial requirements into two hub configurations. This synthesis makes it possible to project the depot space required to accommodate Rotterdam's current reuse ambitions, using the material flow data from Chapter 4.

5 The Spatial Demand of Reuse

Table 5.1 Synthesis of spatial requirements for calculating spatial demand per hub type.

Function	Requirement	Storage Hub	Construction Hub
On-site material storage	Amount of pallets	1 pallet per 10 m ² of stored paving material	1 pallet per 10 m ² of stored paving material
	Stacking height	3 layers	2 layers
	Projected floor area	0.96 m ² per stack of pallets	0.96 m ² per stack of pallets
On-site logistics	Internal circulation	Total area of pallets divided by 0.6	Total area of pallets divided by 0.6
	Loading and unloading area	150 m ²	150 m ²
	Space for mechanical palletisation	0 m ²	200 m ²
On-site additional functions	Office space	50 m ²	50 m ²
	Visitor parking	150 m ²	150 m ²
Site selection	Environmental zoning	≥2	≥4.1

5.3 Spatial Demand of Circular Paving Material Flows

The spatial demand of reuse hubs is calculated from a time-based perspective. The material flows identified in Chapter 4 are distributed across the years in which renovation projects are scheduled. The development of modular paving material flows is shown in Figures 5.3 and 5.4, while the full annual overview is provided in Appendix J.

The figures indicate that fewer projects are scheduled in the later years, reflecting that planning for these years is not yet complete. Based on these flows, the following section calculates peak storage loads, which determine the required floor area.

5.3.1 Assumptions for Defining Peak Storage

Peak storage is defined as the period during which the largest surface area of reusable paving materials is stored simultaneously. This value, rather than the total flows over time, determines the maximum spatial demand for temporary storage. The calculation is based on the following assumptions:

- For each project, the associated surface area of paving material is evenly distributed across the years in which the project is scheduled.
- Total annual inflows and outflows of each paving material are evenly distributed per month.
- A one-month delay applies between material outflow (supply of technically reusable elements) and potential reuse (demand). This means that materials released in January 2025 can only be used from February 2025 onward.
- Stored material accumulates monthly unless completely reused.
- Maximum storage duration is one year; any remaining stock after this period is sent for crushing (inbud), regardless of upcoming demand.
- Stored material is prioritised over new material when fulfilling demand, within the one-year storage limit.
- Standardised materials (SBS-RS, BSS-RS GR, and BSS-RS WB) are matched strictly by type; no substitutions are made between categories.
- Non-standardised materials (BSS-non-RS) are mixed in 50/50 ratios using at least two colour categories. Only such combinations are considered reusable; any remaining material is sent for crushing (inbud).

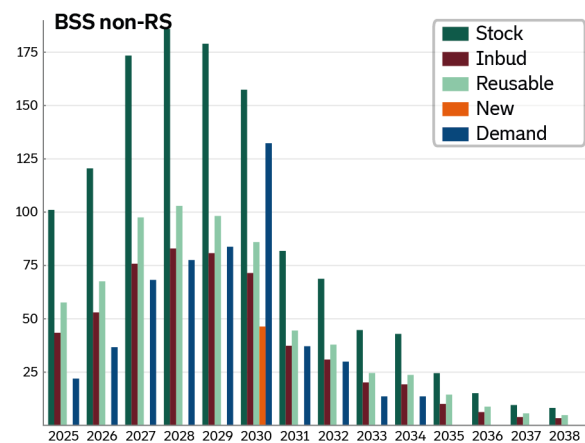
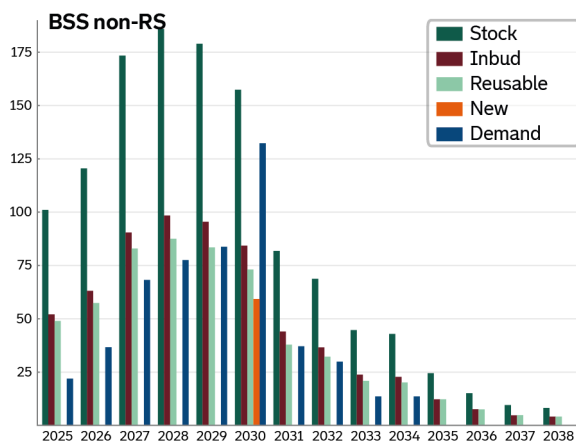
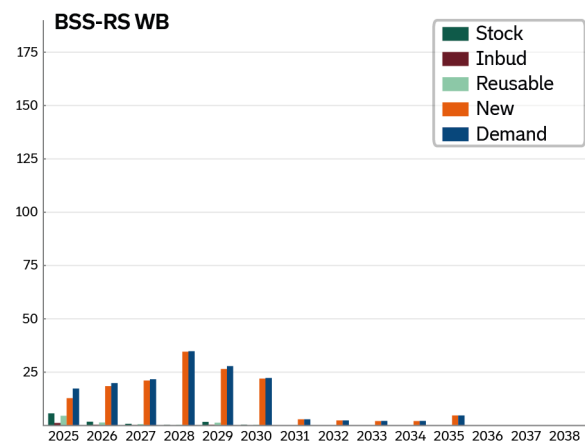
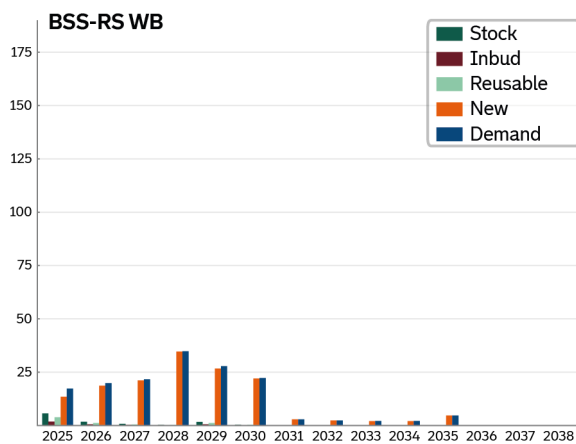
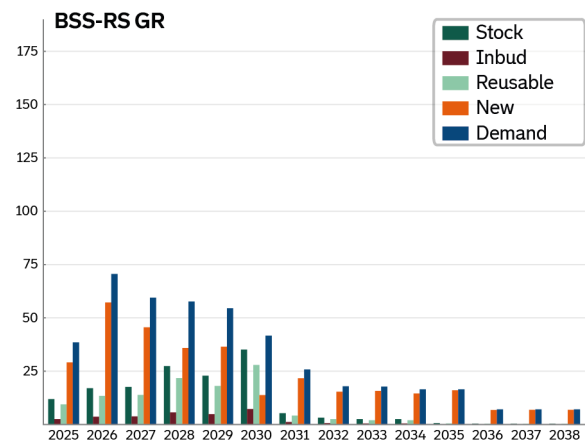
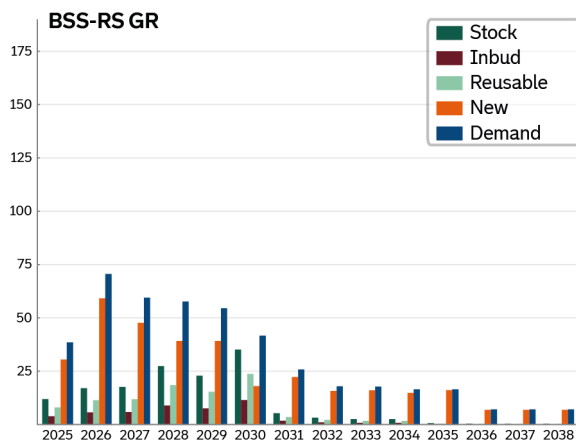
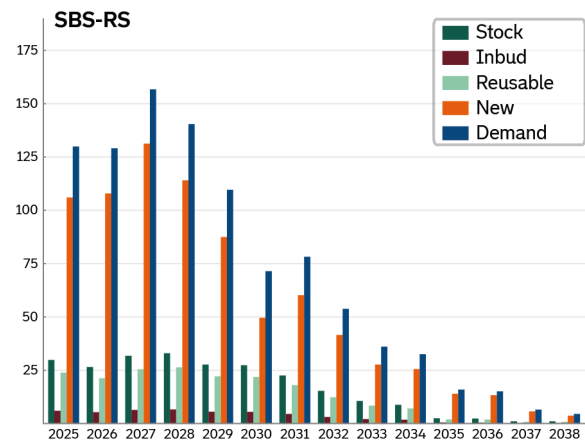
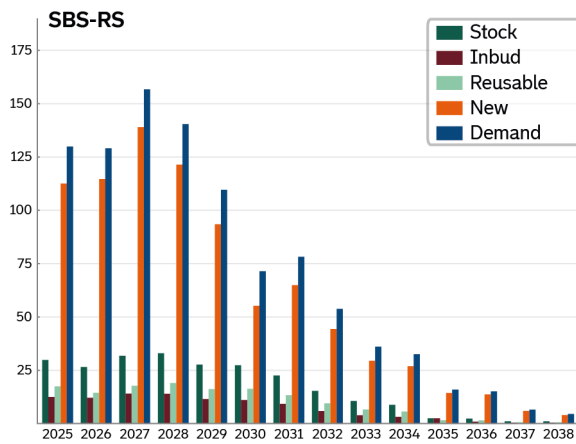


Figure 5.3 Annual modular paving material flows in 1.000 m² under realistic reuse rates.

Figure 5.4 Annual modular paving material flows 1.000 m² under theoretic reuse rates.

5.3.2 Spatial Demand for the Storage Hub

Because demand for standardised paving materials (SBS-RS, BSS-RS GR, and BSS-RS WB) consistently exceeds the technically reusable supply, storage levels remain relatively stable over time. To determine peak load, the monthly storage capacities of these materials are aggregated, as they are stored jointly at the same hub. The developments under the realistic and theoretical reuse rates are shown separately in Figures 5.5 and 5.6. The underlying data for these figures is provided in Appendix K.

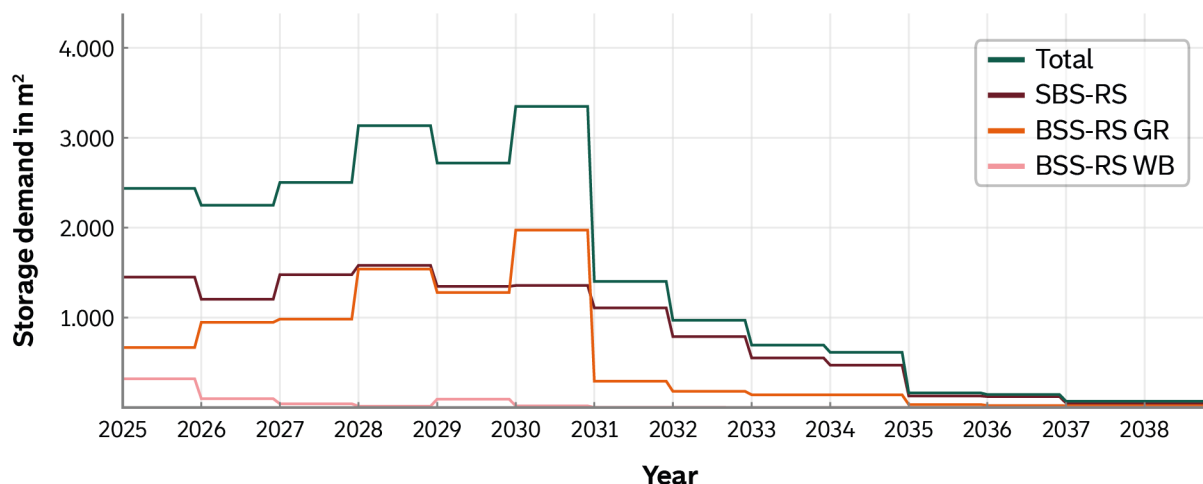


Figure 5.5 Monthly breakdown of storage demand for standardised paving materials under realistic reuse rates.

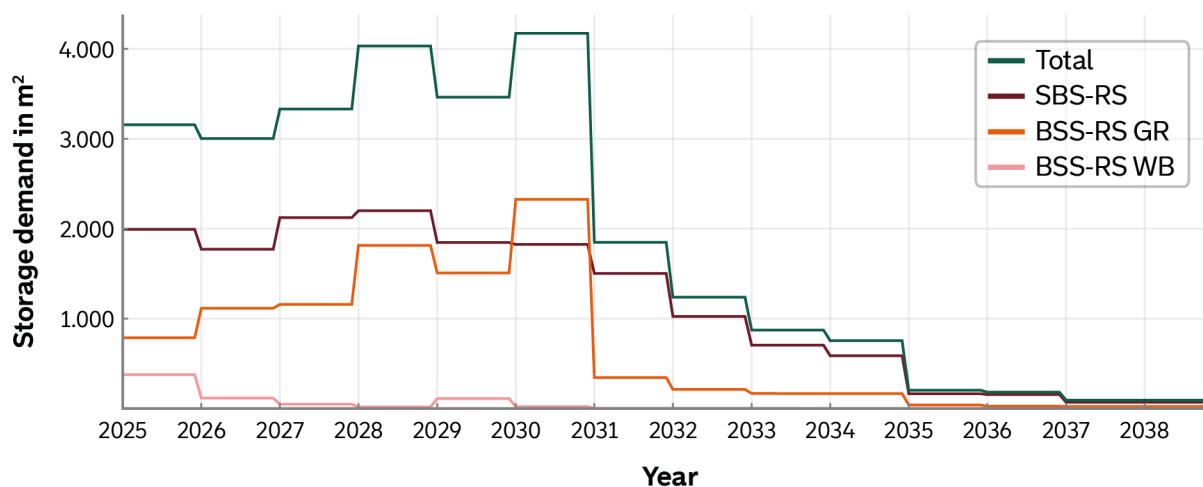


Figure 5.6 Monthly breakdown of storage demand for standardised paving materials under theoretic reuse rates.

Peak storage for both scenarios occurs in 2030, with 3,348.86 m² in the realistic case and 4,167.0 m² in the theoretical case. Applying the spatial requirements defined in Section 5.2, this corresponds to projected floor areas of 617.9 m² and 683.4 m², respectively. This means that even under the theoretical scenario, the required depot space equals roughly one-tenth of a football field, based on the minimum dimensions of 6,400 m² as required by the Dutch Football Association (KNVB, n.d.), illustrating that standardised materials can be stored within compact facilities.

5.3.3 Spatial Demand for the Construction Hub

For non-standardised paving materials (BSS-non-RS), the technically reusable supply is considerably larger than demand, resulting in continuous accumulation in storage. Part of this stock is lost to crushing (inbud) because it cannot be mixed in the required 50/50 ratios or because it exceeds the one-year storage limit. These factors create additional losses, with 85,894.9 m²

directed to crushing under realistic reuse rates and 282,616.2 m² under theoretical reuse rates. The monthly storage demand can be seen in figure 5.7, the underlying data is provided in Appendix L.

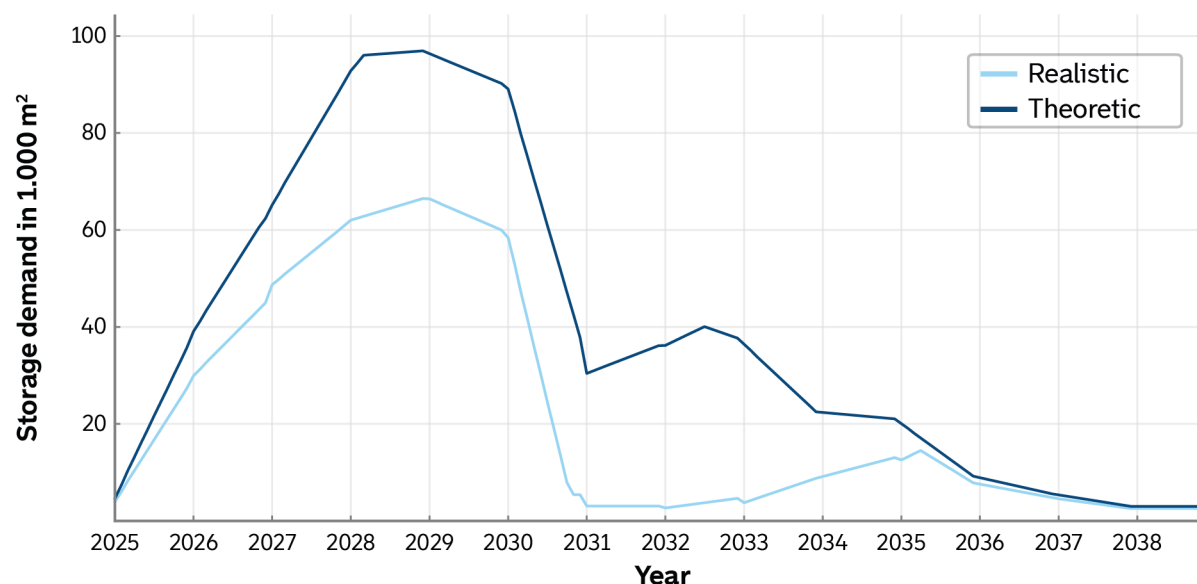


Figure 5.7 Monthly breakdown of storage demand for non-standardised paving materials.

Peak storage occurs in December 2028 for realistic reuse rates (66,487.4 m²) and for theoretical reuse rates (96,946.1 m²). This results in projected floor areas of 5,869.0 m² and 8,305.7 m², respectively. In practical terms, this corresponds to approximately 1 to one and a quarter football fields of space needed (KNVB, n.d.), highlighting the significantly larger footprint required for non-standardised materials.

5.4 Conclusion

The analysis shows that the spatial requirements for circular material hubs differ significantly between hub types. Standardised materials (SBS, BSS-RS GR, and BSS-RS WB) generate relatively stable storage levels that can be accommodated within modest depots. By contrast, non-standardised materials (BSS-non-RS) accumulate structurally over time, creating substantial spatial pressure even after accounting for additional losses to crushing (inbud). Table 5.2 summarises projected floor areas calculate from the peak storage demands for both hub types under realistic and theoretical reuse rates.

Table 5.2 Peak spatial demand of circular storage and construction hubs.

Hub type	Peak moment	Storage demand (m ²)	Spatial demand (m ²)
Storage hub, for SBS, BSS-RS GR, and BSS-RS WB	2030	3,348.86 - 4,167.0	617.9 - 683.4
Construction hub, for BSS-non-RS	December 2028	66,487.4 - 96,946.1	5,869.0 - 8,305.7

These findings underline the spatial implications of Rotterdam's current reuse practices. While standardised materials can be stored efficiently, non-standardised materials require substantially larger depots. Together, these results provide a quantitative foundation for assessing optimisation measures in the following chapter.

Chapter 6

Assessing Adjustment Pathways

The analysis of Rotterdam's circular paving material flows, presented in Chapters 4 and 5, revealed structural mismatches between supply and demand. While significant fractions of standardised paving materials can be reintroduced into municipal projects, non-standard paving blocks accumulate in surplus due to their limited applicability under the Rotterdam Style framework. In addition, monthly fluctuations in supply and demand create temporary pressures that further increase the need for storage capacity.

Qualitative insights from interviews and observations indicate that two main levers exist to optimise Rotterdam's road renovation practices: renovation planning (time) and design choices (material selection). Adjusting either of these aspects, or combining both, offers opportunities for optimisation through three possible adjustments:

1. **The first** targets renovation planning. The previous chapters showed that storing reusable materials generates peaks that increase the spatial demand for storage facilities. To mitigate this, renovation projects can be rescheduled to reduce pressure on storage capacity.
2. **The second** focuses on design. The surplus of non-standard paving blocks (BSS-non-RS) identified in Chapter 4 reflects a mismatch between supply and demand. Although technically reusable, these blocks deviate from the Rotterdam Style framework in colour and dimensions, which restricts their applicability. This adjustment allocates additional locations across Rotterdam where these blocks can be reused.
3. **The third** combines both interventions, first reallocating non-standard materials to suitable locations and then rescheduling renovation projects to minimise temporary storage pressures.

6.1 Adjustments in Project Planning

To reduce temporary storage peaks, renovation projects were rescheduled so that reuse activities are distributed more evenly over time. The average storage requirement for the period 2025–2030 was calculated and used as a maximum reference value to smooth overall demand. Because renovation projects are typically planned according to the end-of-life cycle of sewage systems, only smaller roadwork projects within the 2025–2030 period were adjusted in planning. This approach provides a more realistic estimation of the potential reduction in storage demand without structurally altering long-term maintenance schedules. Years beyond 2030 were excluded due to the lower number of projects and increased uncertainty.

For standardised materials, Figures 6.1 and 6.2 show how adjusted project planning flattens the balance between reusable material supply and demand, underlying data can be found in Appendix M. The maximum achievable flattened storage demand ranges between 2,731.9 m² and 3,521.3 m², which corresponds to projected floor areas for storage hubs ranging from 495.7 m² to 537.8 m². When only smaller projects are rescheduled, the resulting peak for storage demand decreases more modestly, ranging between 2,963.7 m² and 3,795.1 m², corresponding to projected floor areas between 585.9 m² and 653.6 m².

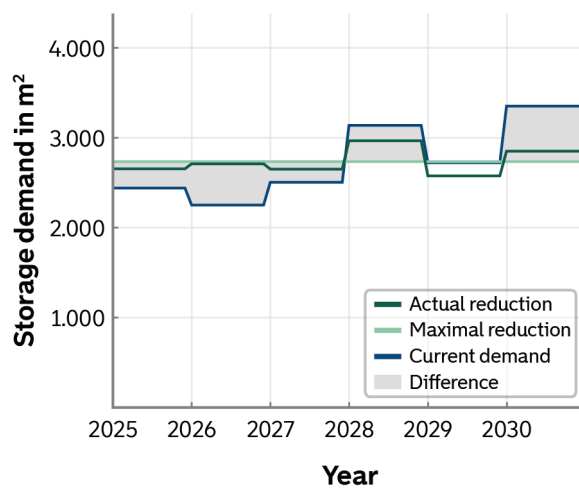


Figure 6.1 Realistic storage demand of standardised materials under adjusted project planning.

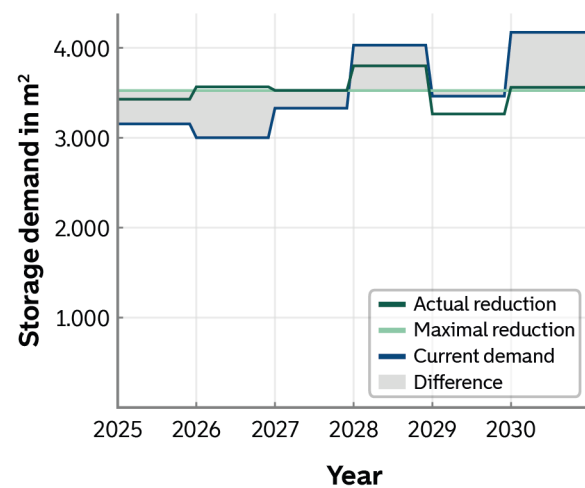


Figure 6.2 Theoretic storage demand of standardised materials under adjusted project planning.

6 Assessing Adjustment Pathways

For non-standard materials (BSS-non-RS), the same adjustment method was applied. Figures 6.3 and 6.4 illustrate how smoothing the project timeline reduces storage peaks, detailed data can be found in Appendix N. The maximum achievable flattened storage demand, reached in December 2028, ranges between 43,980.1 m² and 66,935.7 m², corresponding to projected floor areas between 4,375.3 m² and 6,769.2 m² for construction hubs. When only smaller projects are rescheduled, storage demand ranges between 65,718.2 m² and 96,877.9 m², with projected floor areas between 5,807.5 m² and 8,300.2 m².

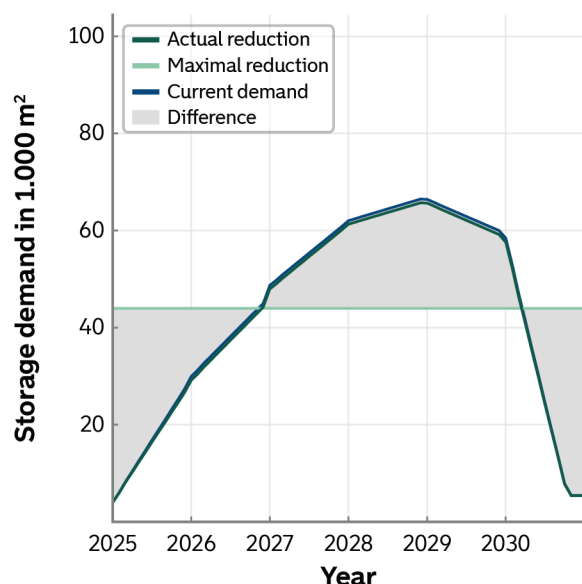


Figure 6.3 Realistic storage demand of non-standardised materials under adjusted project planning.

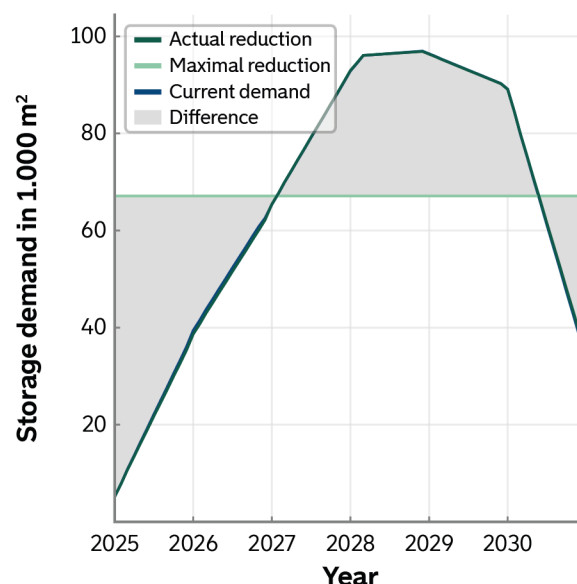


Figure 6.4 Theoretic storage demand of non-standardised materials under adjusted project planning.

The comparison between current reuse ambitions and adjusted project planning is summarised in Table 6.1, which highlights the reduction in projected floor area for both hub types. The results show that adjusted project planning only slightly reduces the spatial demand for storage hubs, by 4.4 - 5.1%, as the yearly distribution of standardised material flows under current practices was already relatively balanced. For construction hubs, the effect is even smaller, with a decrease of 0.1 - 1.0%. The demand for non-standard paving materials remains structurally higher than the available supply, meaning that even when their release is distributed more evenly over the years, accumulation continues to occur. As a result, the one-year maximum storage period has limited impact within the 2025 - 2030 timeframe, and its effect only becomes more pronounced in later years when fewer projects are scheduled.

Table 6.1 Spatial demand under current practices and adjusted project planning.

Scenario	Hub type	Peak moment	Spatial demand (m ²)
Current Reuse ambitions	Storage hub	2030	617.9 - 683.4
	Construction hub	December 2028	5,869.0 - 8,305.7
Adjustments in project planning	Storage hub	2028	585.9- 653.6
	Construction hub	December 2028	5807.5- 8300.2

6.2 Adjustments in Project Design

While rescheduling projects reduces temporal storage peaks, this adjustment focusses on reallocating paving material demand within the Rotterdam Public Space Style Guide Paving Block Map to improve the balance between reusable supply and future demand. Specifically, areas originally designated for BSS-RS GR were reassigned to accommodate BSS-non-RS, increasing the applicability of non-standard paving blocks without altering the zones intended for SBS-RS or BSS-RS WB. To identify where this adjustment could be applied, data from the Basiskaart Groen en Grijs (Green and Grey Base Map) available via the Klimateffectatlas (RIVM et al., 2023) were used to determine the share of green surfaces within public space at both municipal and neighbourhood levels. Based on these data, the average green share was calculated at 53.2 % for Dutch municipalities. Rotterdam neighbourhoods with above-average green ratios, such as Kralingse Bos and Lombardijen, were designated as priority zones for the reuse of BSS-non-RS materials. This approach expands reuse opportunities for non-standard materials in greener environments, where visual uniformity is less critical, while preserving the aesthetic coherence of the Rotterdam Style framework. The resulting allocation is shown in Figure 6.5.

This update only influences the material flows for BSS-RS GR and BSS-non-RS, while the flows for other paving materials remain unchanged. Figures 6.6 and 6.7 show the new flows of these materials between 2025 and 2030; detailed data are provided in Appendix O. In this adjusted scenario, the demand for both BSS-RS GR and BSS-non-RS now exceeds the available reusable amount.

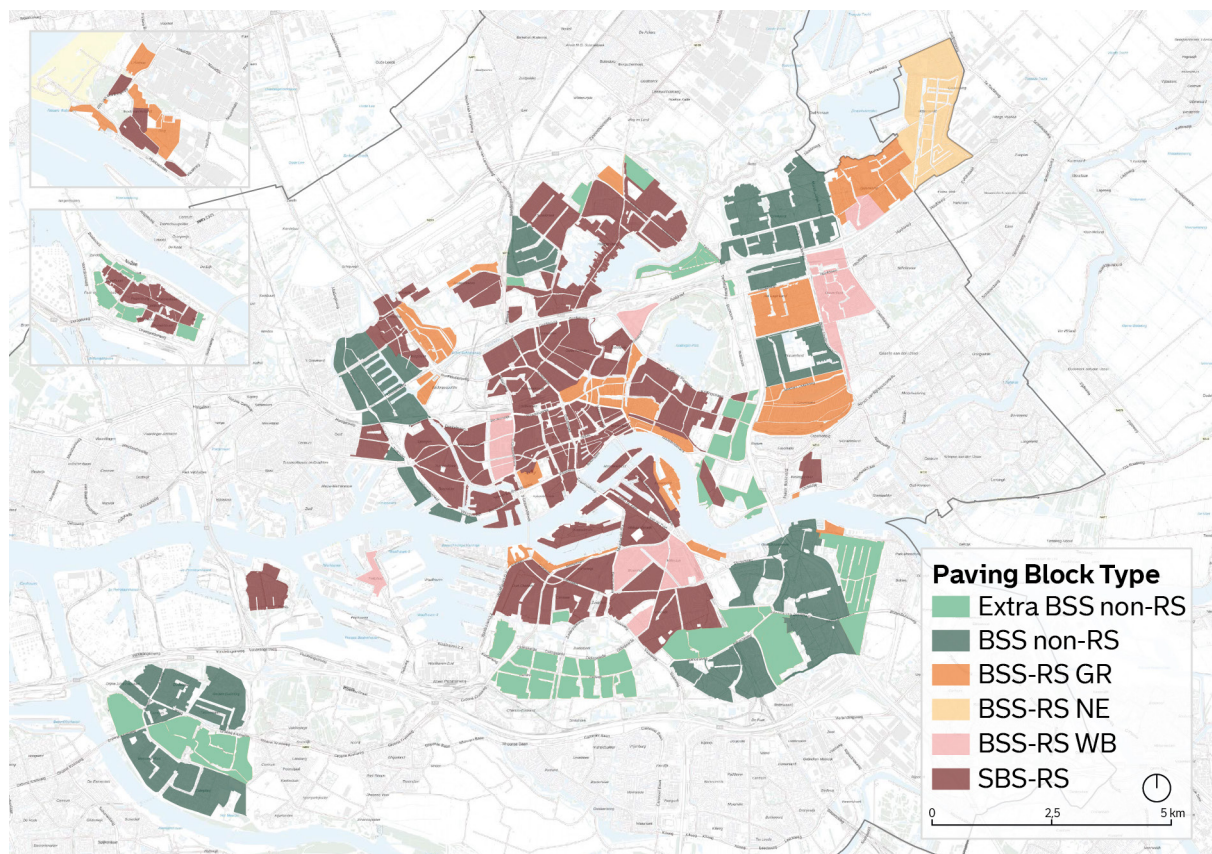


Figure 6.5 Updated version of the Rotterdam Space Style Guide Paving Block Map.

6 Assessing Adjustment Pathways

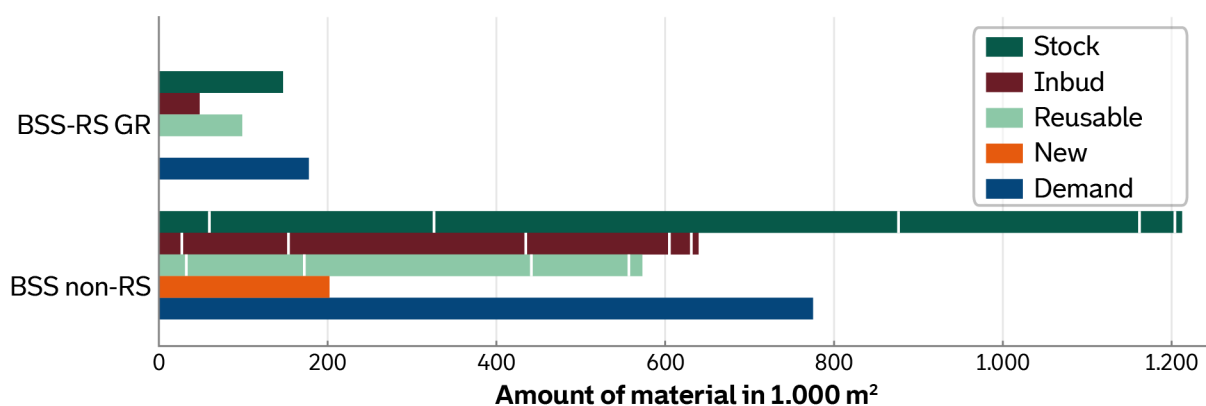


Figure 6.6 Balances of BSS-RS and BSS non-RS after reallocations under realistic reuse rates.

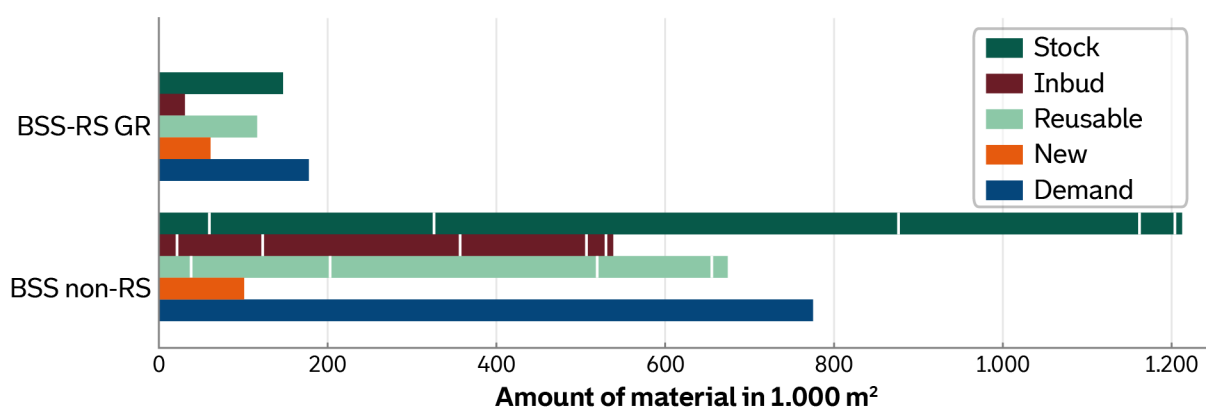


Figure 6.7 Balances of BSS-RS and BSS non-RS after reallocations under theoretic reuse rates.

The comparison between current reuse ambitions and the adjusted project design is summarised in Table 6.2. With the adjusted design, all technically reusable paving materials together account for between 39.2% and 47.4% of total demand. Based on Tables 4.1 and 4.2, this adjustment reduces the consumption of virgin raw materials by 4.6 - 13.0%, corresponding to reductions of 4.4 - 12.5% in CO₂ emissions and 1.5 - 3.8% in total costs.

Table 6.2 Material impact under current practices and adjusted project design.

Scenario	Raw materials (kt)	CO ₂ emissions (kt)	Costs (€ million)
Current reuse ambitions	215.2 - 227.3	17.6 - 18.6	39.6 - 40.8
Adjustments in project planning	187.2 - 213.1	15.4 - 17.5	38.1 - 39.8

Designating additional areas for BSS-non-RS also affects the spatial demand of reuse facilities. For storage hubs, no measurable effect is observed (see Appendix P), as no changes were made to the demand for SBS-RS and BSS-RS WB. However, from 2030 onward, the supply of reusable BSS-RS begins to exceed demand under both realistic and theoretical reuse rates. These surpluses can nevertheless be absorbed by reusing stored BSS-RS in areas designated for BSS-non-RS, as during this period their demand is higher than the amount of stored material and no accumulation of BSS-RS GR occurs.

For construction hubs, the effect is substantial. As demand for BSS-non-RS increases, the material no longer accumulates in large surpluses, and storage levels stabilise compared to current practice. Figure 6.8 illustrates these storage dynamics, with the underlying data provided in Appendix Q. Peak storage occurs in 2028, reaching 6,868.7 m² under realistic reuse rates and 20,536.5 m² under theoretical reuse rates, resulting in projected floor areas of 1,099.5 m² and 2,192.9 m², respectively. This means that the required area for construction hubs decreases from roughly one to one and a quarter football fields under current practices to about a

quarter of a football field under adjustments in project design (KNVB, n.d.). The diagram shows that under realistic reuse rates, surpluses in stored material compared to demand occur only in 2025, whereas under theoretical reuse rates, larger surpluses appear from 2025 to 2027. This explains the considerable difference in storage demand between the two reuse scenarios. For theoretical reuse rates, storage demand caused by accumulating material ceases in February 2028, when surpluses end, and stabilises by September 2029. In both cases, the stored material does not reach the maximum storage period of one year, meaning that all stored material is eventually reused.

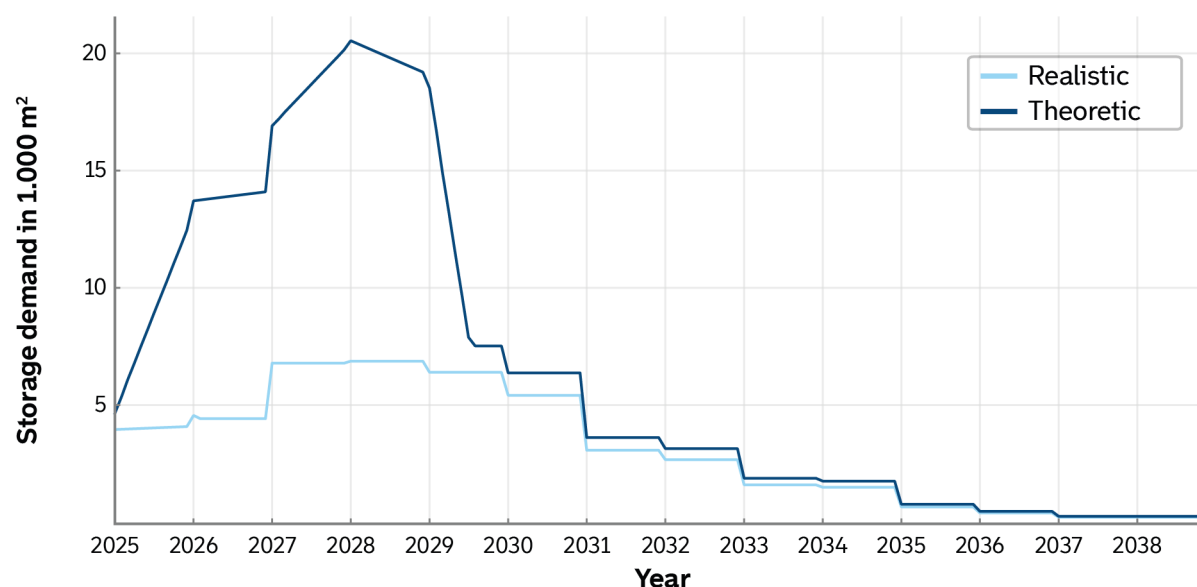


Figure 6.8 Storage demand of non-standardised materials under adjusted project design

The comparison between current reuse ambitions and the adjusted project design is summarised in Table 6.3, which highlights a reduction in projected floor area for construction hubs by approximately 73.6 - 81.2%. These results indicate that reallocating demand within the paving design substantially reduces the spatial demand for construction hubs, as non-standard paving blocks are more effectively reused across the city. For storage hubs, no reduction is observed, since standardised materials were already efficiently distributed under current practices. This demonstrates that spatial efficiency in circular paving practices depends greatly on the flexibility of design standards that determine where and how recovered materials can be reused.

Table 6.3 Spatial demand under current practices and adjusted project design.

Scenario	Hub type	Peak moment	Spatial demand (m²)
Current Reuse ambitions	Storage hub	2030	617.9 - 683.4
	Construction hub	December 2028	5,869.0 - 8,305.7
Adjustments in project Design	Storage hub	2030	617.9 - 683.4
	Construction hub	January 2028	1,099.5 - 2,192.9

6.3 Combining Design and Planning Adjustments

The third adjustment combines the two interventions explored in Sections 6.1 and 6.2, integrating both the rescheduling of renovation projects and the reallocation of material demand between standardised and non-standardised concrete paving blocks. As the design adjustments in Section 6.2 did not affect the spatial requirements of storage hubs, the reduction achieved through planning adjustments in Section 6.1 equally applies here. Therefore, the analysis in this section focuses on BSS non-RS and the resulting spatial demand for construction hubs.

Figures 6.9 and 6.10 show how the combination of planning and design adjustments affects storage demand for construction hubs compared to the individual adjustments. The underlying data are provided in Appendix R. Peak storage demand can be maximally reduced to 5,650.7 m² under realistic reuse rates and 13,006.8 m² under theoretical reuse rates, corresponding to projected floor areas between 1,002.6 m² and 1,590.5 m² for construction hubs. When applying the same rescheduling method as in Section 6.1, the actual peak storage, reached in 2028, ranges between 6,863.9 m² and 18,149.4 m², corresponding to projected floor areas of 1,099.1 m² and 2,002.0 m², respectively.

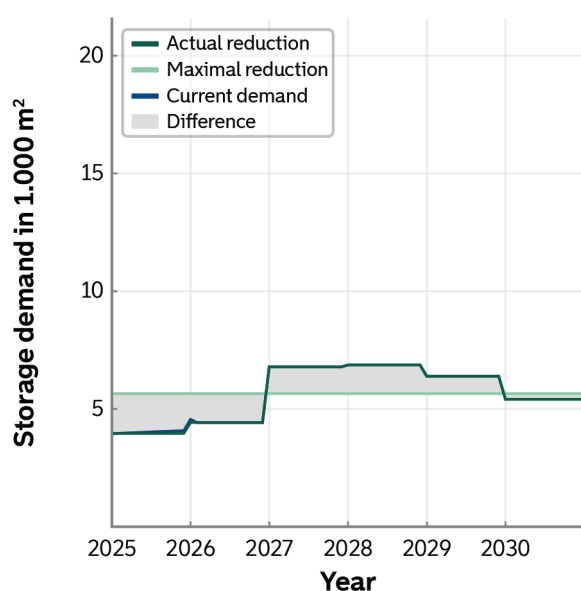


Figure 6.9 Realistic storage demand of non-standardised materials under combined planning and design adjustments.

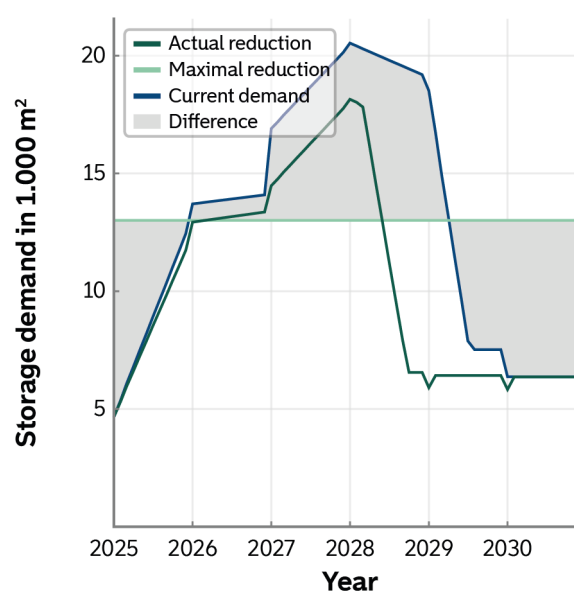


Figure 6.10 Theoretic storage demand of non-standardised materials under combined planning and design adjustments.

Table 6.4 summarises the comparison between current practices and the combined approach. The results indicate that this integrated adjustment achieves the greatest reduction in spatial demand, particularly for construction hubs, with a reduction of approximately 75.9 - 81.3%, as it addresses both the timing and design dimensions of material reuse.

Table 6.4 Spatial demand under current practices and combined planning and design adjustments.

Scenario	Hub type	Peak moment	Spatial demand (m ²)
Current Reuse ambitions	Storage hub	2030	617.9 - 683.4
	Construction hub	December 2028	5,869.0 - 8,305.7
Combined Adjustments	Storage hub	2028	585.9- 653.6
	Construction hub	January 2028	1,099.1 - 2,002.0

6.4 Conclusion

The analysis shows that design and planning adjustments influence secondary paving material use in complementary but uneven ways. Rescheduling projects helps to reduce temporary storage peaks and slightly lowers spatial demand, while adjusting project design increases the applicability of non-standard paving materials and reduces the need for virgin resources. In contrast, combining planning and design adjustments produces only marginal additional benefits, as most improvements already result from design adjustments alone. Table 6.5 summarises the outcomes of all four configurations, highlighting how different combinations of planning and design choices shape material balances and spatial requirements.

In summary, adjusting design practices within the Rotterdam Style framework provides the greatest leverage for circular paving material reuse. By expanding the application range of non-standard materials, it not only improves material efficiency and its related impact but also significantly reduces spatial demand. While rescheduling projects supports these outcomes by levelling storage peaks, its overall impact on spatial demand remains limited. Moreover, project scheduling is subject to greater uncertainty and dependency on other infrastructure cycles. Together, the findings indicate that design flexibility, rather than planning, should be prioritised when optimising circular material reuse in municipal road renovation.

Table 6.5 Material and spatial impacts under current practices and adjustment pathways.

	Current Planning			Adjusted Planning		
	Material	Reuse share (%)	36 - 40	Material	Reuse share (%)	36 - 40
Current Design		Raw materials (kt)	215 - 227		Raw materials (kt)	215 - 227
		CO ₂ (kt)	18 - 19		CO ₂ (kt)	18 - 19
		Costs (€ million)	40 - 41		Costs (€ million)	40 - 41
	Spatial	Storage hub (m ²)	618 - 683	Spatial	Storage hub (m ²)	586 - 654
Adjusted Design		Construction hub (m ²)	5,869 - 8,306		Construction hub (m ²)	5,808 - 8,300
	Material	Reuse share (%)	39 - 47	Material	Reuse share (%)	39 - 47
		Raw materials (kt)	187 - 213		Raw materials (kt)	187 - 213
		CO ₂ (kt)	15 - 18		CO ₂ (kt)	15 - 18
		Costs (€ million)	38 - 40		Costs (€ million)	38 - 40
	Spatial	Storage hub (m ²)	618 - 683	Spatial	Storage hub (m ²)	586 - 654
		Construction hub (m ²)	1,100 - 2,193		Construction hub (m ²)	1,099 - 2,002

Chapter 7

Discussion

This chapter interprets the results of the preceding analyses and situates them within broader conceptual and methodological contexts. It begins with a critical interpretation of the findings, structured around three interrelated themes that illustrate how circular ambitions manifest in practice. The discussion then connects these insights to the theoretical concepts introduced earlier. Finally, the chapter reflects on the methodological approach, addressing its limitations and implications for scalability.

7.1 Interpretation of Results

This research addresses the problem defined in Chapter 1: the lack of quantitative insight into the spatial requirements of circular practices. Municipalities are increasing their efforts to reuse paving materials in their renovation practices, yet the spatial and logistical consequences of doing so remain poorly understood. By quantifying storage and processing demand in Rotterdam, this study tries to make these implications tangible and shows how design norms, planning routines, and material standards together shape the physical footprint of circularity. The following sections interpret these findings through three themes: the role of standardisation in enabling and constraining reuse, the accumulation of stored materials and resulting spatial demand, and the opportunities for optimisation within existing design and planning frameworks.

7.1.1 Standardisation as Enabler and Constraint

Results show that paving material reuse ambitions are shaped across the municipality's road maintenance and public space design policies, the latter defining which materials may be reused within a broad framework of standardised types and their spatial allocation across Rotterdam. The drive to standardise paving materials stems primarily from aesthetic considerations, aiming to create a uniform and high-quality appearance across the city while facilitating future

reuse through consistent dimensions and performance. A limited and coherent material palette simplifies recovery and redistribution, as components can be reapplied in different locations without technical mismatch. In this way, standardisation provides the logistical foundation for large-scale reuse.

At the same time, this coherence restricts the reuse of older, non-standard materials that pre-date current norms. These paving blocks, which make up a large share of the city's reusable stock, are less in demand because they no longer fit the aesthetic conventions of today's design framework. As a result, the actual level of reuse remains lower than what is technically feasible. If current policy remains unchanged, the same pattern is likely to reoccur in the future. As innovation in paving materials advances and new, more sustainable options become available, integrating them into the standard palette could strengthen environmental performance. Yet doing so would simultaneously risk making the current standard materials obsolete, creating a new generation of surplus stock.

Beneath this lies a cultural bias toward novelty. Interviews and observations indicate that even when recovered materials meet technical and aesthetic criteria, new products are still perceived as cleaner, more reliable, and more representative of quality. This preference reinforces linear tendencies within otherwise circular frameworks. The boundary between circular and linear practice is therefore not determined by technical capability, but by institutionalised perceptions of value, order, and appearance.

7.1.2 Spatial Demand Defined by Material Surpluses

The analysis distinguishes two types of reuse infrastructure relevant to Rotterdam: storage hubs for standardised materials that can be palletised directly at renovation sites, and construction hubs for non-standard materials that require additional mixing and processing. Their functional requirements are largely comparable, each requires space for storage, access, and handling, but they differ mainly in stacking height and the need for material processing. Consequently, differences in total spatial demand arise not from the facilities themselves but from storage pressure, which increases as materials accumulate over time.

Rotterdam's current reuse ambitions therefore create not only a conceptual challenge but also a tangible spatial one. This is mainly driven by older, reusable non-standard paving blocks, whose supply structurally exceeds demand, resulting in a persistent material surplus. Standardised materials, by contrast, generate stable and predictable storage needs because they can be readily reintegrated into ongoing projects. The contrast is considerable: under realistic reuse rates, non-standard paving blocks require nearly ten times more storage space than standardised ones, equivalent to a single football field dedicated solely to the storage paving materials under realistic reuse rates. As long as policy ambitions for reuse include non-standard materials without adjusting design priorities, the spatial demand for reuse infrastructure will keep increasing.

7.1.3 Optimization of Reuse through Design Practices

By defining the circular material flows and the resulting spatial demand for reuse infrastructure, this study established a baseline for Rotterdam's current ambitions and practices. Based on this, three adjustment pathways were explored: adjustments in project planning, adjustments in project design, and a combination of both. Not all pathways proved equally effective. Planning adjustments showed limited impact: although rescheduling renovation works was expected to smooth temporary storage peaks, planning flexibility remains constrained. Maintenance schedules are closely tied to sewer replacement cycles and lifespan-based planning, limiting the even distribution of storage demand. As a result, the reductions in spatial demand were minor.

Design adjustments hold the greatest potential to align circular ambitions with practical implementation. Widening design boundaries, by allowing non-standard paving blocks to be reu-

sed in greener or less visually uniform areas, significantly increases their applicability, enabling reusable stock to meet demand rather than accumulate in storage. This lowers the need for new materials across all paving types and reduces the spatial demand for reuse hubs by more than eighty percent. Advancing circularity therefore depends largely on the willingness to reconsider design norms. Integrating reuse considerations requires a cultural shift in how material value and urban quality are perceived, transforming circularity from a technical goal into a guiding design principle. In practice, this means embracing a streetscape that may appear less uniform but better reflects the physical realities of a circular policy.

7.2 Conceptual Reflection

This section reflects on how circularity in infrastructure can be understood through the theoretical concepts introduced in Chapter 2. While most circular construction research focuses on material innovation at the building scale, less is known about how circularity operates within infrastructural systems and municipal maintenance regimes. The following analysis applies key spatial and governance concepts, such as the re-supply chain, territorialising circularity, and the multi-level perspective, to interpret these dynamics.

7.2.1 Translating Spatial Circularity Concepts to the Rotterdam Case

The concept of the re-supply chain, defined by Van den Berghe and Verhagen (2021) as a circular production system in which materials re-enter the value chain through cycles of recovery, remanufacturing, and reapplication, provided a useful starting point for this research. However, the findings indicate that the re-supply chain for modular paving materials differs fundamentally from that described in building-scale contexts. Because these materials are homogeneous and modular by design, they can be directly reintegrated into the same urban system with minimal processing, reducing the need for remanufacturing. In Rotterdam, the mixing of older non-standard paving blocks represents the most extensive form of processing required, while in Haarlem only minor cleaning is needed before palletising, and in Apeldoorn no processing occurs at all. As a result, the re-supply chain for paving materials is characterised less by transformation and more by deconstruction, storage, and reconstruction, a continuous operational loop that reflects the repetitive nature of municipal maintenance rather than the one-off recovery cycles typical of building-scale reuse.

Because the re-supply chain for modular paving materials is far simpler than that of building components, the definition of reuse infrastructure is likewise more straightforward. Whereas Tsui et al. (2024) and Van Uden et al. (2025) describe circular building hubs as multi-functional facilities that combine dismantling, remanufacturing, and marketplace activities, such diversity of functions is largely absent for paving materials. In Rotterdam, this is mainly due to the continuity of ownership: the materials remain municipal property before, during, and after reuse, meaning that only one stakeholder is involved. As a result, reuse facilities operate primarily as logistics nodes, which rather than multifunctional hubs. This nuances Van Uden et al.'s (2025) view of circular building hubs as temporary instruments expected to evolve into lighter, logistics-oriented interfaces once circularity is more established, as hubs for paving materials may already represent this form. Embedded within continuous maintenance cycles rather than project-based construction, these facilities remain essential yet modest in scope, focused on stabilising material flows within municipal operations rather than replacing existing logistics systems.

Furlan et al.'s (2022) notion of territorialising circularity provides an interesting perspective for this study, as it emphasises that circularity must be grounded in the regulatory and physical realities of place rather than treated as an abstract material network. The concept is particularly relevant when considering where reuse infrastructure should be located within urban or regional systems. However, at the scale of Rotterdam, where available land is scarce, the question is not so much where such infrastructure could best be placed, but whether it can be accom-

modated within the city at all, and how much space it requires. This suggests that, for modular paving materials at the urban scale, the principle of territorialising circularity might translate into a more quantitative approach, one that focuses on assessing spatial demand rather than identifying optimal locations.

7.2.2 Dynamics of Paving Material Reuse through MLP

Seen through Geels's (2011) multi-level perspective, the reuse of paving materials functions as a niche innovation that is still attempting to embed itself within a stabilised regime of standardised procurement, rigid design codes, and cultural expectations of uniformity that reinforce linear material flows. Establishing reuse infrastructure and quantifying its spatial requirements therefore represent necessary but not sufficient conditions for achieving circularity. Even if sufficient space were reserved for all reusable paving blocks, circularity would not automatically follow. Without corresponding adjustments in procurement logic, accountability structures, and design standards, these facilities risk reproducing linear inefficiencies under a circular label. What this study reveals is that understanding how much space is needed and which institutional choices shape that demand is a critical starting point, but circularity will only become the norm once spatial, organisational, and cultural systems evolve together. As long as this institutional alignment remains limited, reuse infrastructure will continue to compensate for, rather than transform, the stability of the existing regime.

7.3 Methodological Reflection

This section reflects on the methodological choices that shaped the study and their implications for reliability and transferability. The research applied a quantitatively driven mixed-methods design to address the limited empirical understanding of the spatial requirements of circular practices. Quantitative modelling provided measurable insight into material flows and spatial demand, while qualitative data were used to define system boundaries and interpret institutional context. Together, these methods linked material behaviour with policy and planning logic. The following sections discuss the main limitations of the quantitative and qualitative components and reflect on how the research scope affects the broader applicability of the approach.

7.3.1 Limitations for Quantitative Data and Analysis

The quantitative approach builds on earlier MFA studies, notably Van den Berghe and Verhagen (2021), whose work on secondary concrete flows in The Hague offered a methodological precedent at a comparable municipal scale. This method was selected for both its conceptual fit and its compatibility with the data available in Rotterdam. The analysis drew on three spatial datasets: Road Segments (material stocks), Rotterdam Style Paving Block Map (material demand), and Planned Renovation Projects (timing of material flows). While these datasets allowed straightforward integration in GIS, they varied considerably in spatial resolution. The detailed Road Segments data often misaligned with the coarser Rotterdam Style and Planning layers, causing minor inconsistencies in material allocation. Such discrepancies stem from data resolution and software limitations but do not undermine overall reliability.

Because only a few datasets were available, the outcomes depend strongly on their validity. The Rotterdam Style Paving Block Map, updated with municipal input, reflects current ambitions but may lose relevance if policy priorities change. The Road Segments data likely contain minor inaccuracies, and the absence of colour information for older materials required approximations based on construction year. Recovery rates from literature were adjusted downward after expert feedback, yet they remain assumptive in the absence of local data. Together, these datasets provide an indicative, not exact, representation of circular material flows.

The Planned Renovation Projects dataset introduces the most uncertainty. Its projected decline in activity conflicts with broader sector expectations of increasing maintenance demand (Arnoldussen et al., 2022), suggesting that late-year projections are incomplete. Moreover,

smaller unplanned works, often triggered by material damage or failure, were not included, even though these could have reduced the calculated storage demand, as recovered materials from such repairs are typically reused immediately. The additional assumption that all projects generate reusable materials and release them evenly over time further limits precision. Consequently, the calculated storage demand should be interpreted as indicative rather than exact.

Several limitations also arise from the way the adjustment pathways were developed. Because of the structure of the Planned Renovation Projects dataset, it was difficult to distinguish which projects could realistically be rescheduled and which were bound by end-of-life criteria. As a result, the estimated benefits of the planning and combined pathways should be interpreted with caution. The analysis of design adjustments was likewise simplified, as it relied on the dataset by RIVM et al. (2023), which estimates the share of green and paved surfaces in public space based on satellite imagery. Although this provides a consistent citywide overview, it does not differentiate between qualitative types of green space or their social value. This limitation is reflected in the updated Rotterdam Style Paving Block Map (Figure 6.5), where garden cities in the southern part of Rotterdam, historically areas with socio-economic disadvantages (Custers & Willems, 2024), are identified as suitable locations for reusing non-standard materials. From a spatial justice perspective, this raises concerns about distributive justice (Rocco, 2022).

7.3.2 Limitations for Qualitative Data and Analysis

The qualitative analysis served a supportive role, intended to contextualise and inform the quantitative results. The combined analysis of policy documents and interviews clarified institutional frameworks, while the site visits, supported by desk research, provided grounded insights into the spatial characteristics of reuse facilities. Due to this guiding rather than leading role, the empirical scope of the qualitative research remained limited and was therefore more susceptible to interpretive bias on the part of the researcher.

Regarding the definition of municipal practices, the interviews were conducted exclusively with senior officials and circularity specialists within the Municipality of Rotterdam. Including junior landscape designers could have provided a more practice-oriented perspective on how design choices and policy constraints interact in daily work. Similarly, interviews with operational staff involved in on-site road maintenance might have revealed practical barriers and enablers of material reuse that remain underexplored in this study. Given the small sample size, the qualitative material was analysed inductively rather than through formal coding. This interpretive approach was appropriate for an exploratory study but inevitably introduces a degree of subjectivity.

For the definition of spatial requirements, only two existing reuse facilities, located in Apeldoorn and Haarlem, were visited. These sites offered valuable first-hand reference points but were relatively similar in how they handled paving materials. It would have been highly valuable to visit a more technologically advanced hub, such as those emerging in Amsterdam (Keuchenius, 2025), to better understand operational diversity and innovation potential. Furthermore, the visited municipalities differ from Rotterdam in scale, local context, and institutional maturity, which limits the generalisability of the findings. Observations during site visits were momentary rather than longitudinal, meaning that operational practices were interpreted based on single-day impressions and discussions with site representatives. While these observations provided useful spatial and organisational benchmarks, they may not capture all aspects of daily operation. The combination with desk research proved complex: many of the additional sources originated from suppliers or technical practitioners, offering valuable but context-specific information. As a result, the derived spatial characteristics may reflect particular operational models rather than universally applicable practices.

7.3.3 Research Scope and Implications for Scalability

This research was conducted entirely within the municipal context of Rotterdam, where the analysis focused on the operational scale of road infrastructure management. Almost all quan-

titative and qualitative data originated from the municipality itself, with the exception of information used to define the spatial requirements of reuse infrastructure. This municipal focus ensured a high level of data consistency and institutional relevance, allowing for a detailed assessment of how circular principles can be applied within existing maintenance and design frameworks. However, this same focus also limits the external validity of the findings. The study's outcomes are tightly linked to Rotterdam's specific policy instruments, design standards, and data systems, which means that direct generalisation to other urban contexts requires careful adaptation.

Despite this contextual specificity, the research design itself is highly reproducible for other municipalities. The analytical framework, combining municipal datasets such as material passports of roads, design guidelines for material use, and long-term maintenance agendas, can be replicated wherever such datasets are available. The qualitative component is loosely coupled to the quantitative structure, meaning that document analysis and interviews can be locally adapted without affecting the overall methodological sequence. As a result, the mixed-methods approach presented here offers a transferable template for studying material reuse at the municipal level. Nevertheless, its applicability is limited to modular paving materials, which can be readily recovered, stored, and reapplied within circular construction systems.

Chapter 8

Conclusion

This final chapter synthesises the main insights derived from the research. The study examined how Rotterdam's current road renovation practices influence the reuse of paving materials and what spatial implications arise from these practices. The chapter serves two purposes. First, it revisits and answers the main and sub-research questions defined in Chapter 1. Second, it translates these findings into recommendations for both Rotterdam and other Dutch municipalities, and directions for future research.

8.1 Answering the research questions

8.1.1 Sub Research Questions

How do Rotterdam's current road renovation practices and reuse ambitions shape the scale and composition of circular paving material flows?

Rotterdam's circularity policy is comprehensive at the municipal level, with explicit ambitions to open dedicated reuse depots and reduce primary material consumption. However, existing reuse hubs remain small and temporary. Two interrelated practices shape material flows: maintenance planning and design regulation. Maintenance planning is primarily guided by sewer replacement cycles. When subsidence or sewer deterioration occurs, streets above are renewed as integrated projects, with interim maintenance at mid-cycle intervals. In design, the Rotterdam Public Space Style Guide has, since the early 2000s, standardised paving materials citywide to achieve a uniform, high-quality public realm.

When these practices are translated into quantified circular material flows, results show that not all technically reusable materials are ultimately reused. Between 84 % and 93 % of reusable materials are actually reapplied, meaning that current practices do not yet fully exploit their circular potential. This is mostly due to the fact that older non-standardised concrete paving

block, predating the establishment of the Rotterdam Style framework, currently form a large share of the stock flowing out of renovation projects, and the demand for them is lower than their supply. While for the standardised materials the supply of technically reusable materials fall makkelijk within their demand.

What is the spatial demand of reuse infrastructure under Rotterdam's current road renovation practices?

Two types of reuse infrastructure were defined for Rotterdam. Storage hubs provide space for temporary storage of standardised materials that can be palletised and cleaned directly on-site, while construction hubs handle non-standard materials that require additional colour-mixing and processing before reuse. Their spatial configurations are similar, differing mainly in pallet-stacking height and the space required for handling operations. Calculations show that standardised materials require limited depot space, approximately 0.6 ha, whereas non-standard materials demand up to ten times more. This difference arises from structural accumulation: the supply of technically reusable, non-standard materials consistently exceeds demand under current municipal practices, resulting in growing storage needs rather than operational inefficiencies of the hubs themselves.

In what ways can Rotterdam's road renovation practices be adjusted to optimise paving material reuse and its associated spatial demand?

Building on the findings above, three adjustment pathways were modelled and tested: planning, design, and combined adjustments.

- **Planning adjustments**, redistributing renovation projects more evenly across years, slightly reduced storage peaks by roughly 4–5 %.
- **Design adjustments**, reallocating demand by allowing non-standard paving blocks to be reused in more areas of the city, had the largest effect, reducing spatial demand for construction hubs by 73–81 % and making sure that all reusable materials are completely reused.
- **Combined adjustments** provided only marginal improvement beyond design adjustments alone.

These results indicate that design flexibility, rather than rescheduling of projects, is the main lever for both environmental and spatial optimisation.

8.1.2 Main Research Question

How do Rotterdam's road renovation practices enable the systematic reuse of paving materials while managing the spatial demand this creates?

The findings show that Rotterdam's road renovation and design standards enable reuse primarily through standardisation, which simplifies recovery and redistribution. Yet, the same standardisation constrains circular potential by excluding non-standard materials from reuse, leading to structural surpluses and associated spatial pressure. Spatial implications are therefore driven not by the footprint of reuse facilities themselves, but by the material oversupply that accumulates under current design norms. Among the explored strategies, adjustments within the Rotterdam Style design framework offer the greatest potential for optimisation, demonstrating that circular efficiency in municipal road renovation depends less on additional storage capacity and more on adaptive design standards that determine where and how recovered materials can be reused.

8.2 Recommendations

8.2.1 Recommendations for Rotterdam

Reassess design standards

While the standardisation of paving materials under the Rotterdamse Stijl supports future circularity by limiting material diversity, it simultaneously constrains current reuse potential. The reuse of non-standard materials is often dismissed on aesthetic grounds, without clear evidence that the resulting visual quality is inferior to that of new materials. Further empirical research and on-site assessments should explore where aesthetic flexibility could be accepted and how citizens actually perceive reused materials. The thesis has already identified neighbourhoods with greener or more informal spatial typologies where non-standard materials could be reintroduced. A more spatially just approach would require visiting and documenting different urban environments to understand where aesthetic standards genuinely enhance, or unnecessarily restrict, circular practice. In this context, the applicability of SBS-RS paving types beyond their current zones could be reconsidered.

Structure storage and logistics

Rotterdam would benefit from establishing at least one permanent, centrally located construction hub dedicated to the sorting, processing, and redistribution of non-standard materials. Given their higher environmental zoning requirements, such facilities should be located on industrial sites and integrated into long-term spatial planning. In contrast, storage hubs for standardised materials may remain temporary or be embedded within redevelopment areas, similar to the Apeldoorn example. To improve coordination, the municipality should develop an internal digital platform linking material passports and GIS layers, enabling real-time monitoring of material flows and depot capacity. Clear institutional ownership is crucial. A dedicated municipal unit, should be assigned the mandate to coordinate secondary material flows across departments. This unit could function as a central intermediary between design, procurement, and maintenance divisions, ensuring that reuse targets are translated into operational practice.

8.2.2 Recommendations for Dutch Municipalities

Modular paving materials form a relatively homogeneous material stream that can be directly reused without extensive processing. This makes them a valuable starting point for municipalities seeking to operationalise circularity within public space management.

Integrate circularity early in project preparation

Circularity should be embedded at the earliest stages of project development, ideally within the design phase rather than postponed to procurement or execution. Explicitly requiring the reuse of recovered materials in project briefs ensures that design choices, material specifications, and planning timelines are aligned with circular ambitions from the outset.

Reserve physical space for reuse infrastructure

Municipalities should include reuse infrastructure within their spatial and environmental plans, treating it as a form of essential urban infrastructure comparable to energy or waste systems. Allocating space for construction or storage hubs within industrial zones or redevelopment sites allows for predictable and long-term integration of reuse logistics into the built environment.

Develop and refine design standards

Municipalities that do not yet possess comprehensive design guidelines for public space, such as Rotterdam's Public Space Style Guide, should establish them. Standardising material palettes reduces unnecessary variation in future paving materials, thereby simplifying reuse cycles. At the same time, attention should remain on the materials that are already in stock, ensuring that design strategies address existing rather than only future material flows.

Digitalise material data and connect it to practice

Where resources permit, municipalities are encouraged to create digital material passports for public space assets. Such inventories provide insight into the existing material stock and its condition, enabling better coordination between maintenance planning and reuse potential. When datasets on street segments, material standards, and maintenance schedules are available, the analytical method used in this study becomes fully reproducible. Combining material flow analysis with policy and practice data helps identify bottlenecks in circular operations that are otherwise difficult to quantify.

Collaborate regionally

Finally, municipalities should cooperate across administrative boundaries to balance material supply and demand at the regional scale. Sharing stock and demand data across municipalities can mitigate local material shortages, reduce storage requirements, and generate economies of scale. Regional collaboration also strengthens collective learning and creates a more resilient network for circular resource management.

8.2.3 Recommendations for Future Research

This study has addressed a specific and relatively homogeneous material stream, modular paving blocks, and has thereby only captured a fraction of the spatial and institutional complexity of the circular transition in urban infrastructure. Several directions for future research emerge from the findings and limitations of this work.

Aesthetic quality and public perception

A recurring but unresolved theme in this study concerns the aesthetic dimension of material reuse. The assumption that reused paving materials inherently result in lower visual quality has not been empirically substantiated. Future research could therefore assess how the aesthetic perception of reused materials differs from that of new ones, and how these perceptions influence municipal design and procurement decisions. Such research would benefit from combining technical assessments of material quality with behavioural and socio-cultural analysis, exploring how citizens, designers, and policymakers perceive visible circularity in the public realm. Understanding these dynamics could help to reframe the aesthetic dimension of circularity from a perceived limitation into a social and cultural asset.

Quantifying the spatial demand of the circular transition

The research began from the broader observation that the spatial requirements of the circular transition remain poorly understood. Literature and data sources that quantify the physical space needed for reuse infrastructure are limited. This study has responded by developing its own set of spatial requirements, but only for modular paving materials. Future research should extend this approach to more heterogeneous material flows, such as concrete, asphalt, or street furniture, and potentially to building materials and other urban sectors. Expanding the model would allow for a more comprehensive quantification of how circular material practices translate into spatial demand across the built environment.

Regional governance and multi-actor complexity

The local scope of this study simplified ownership and logistical relations, as all materials remained under municipal control. When scaling up to a regional or inter-municipal level, complexity increases substantially. Ownership structures diversify, transport distances lengthen, and governance arrangements become more fragmented. It would be valuable to investigate how inter-municipal collaboration for material reuse could be organised in practice, what institutional or regulatory barriers currently exist, and what mechanisms, such as shared material markets or regional planning instruments, could enable cooperation. Understanding these dynamics is essential to facilitate circularity at the scale where material flows and economic networks actually operate.

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Appendix A Literature Review of Innovations within the Infrastructure Sector

Substitution

Hanemaaijer et al. (2023) define the “Substitution” strategy as the replacement of primary raw materials with sustainably produced, renewable alternatives or less environmentally damaging materials. This section discusses potential alternative materials for the three most commonly used paving types in the Netherlands: asphalt, concrete paving blocks, and bricks.

Asphalt Paving

Asphalt recycling is already widespread, with Reclaimed Asphalt Pavement accounting for up to 95% of new asphalt mixes. However, the dominant techniques used in the Netherlands, hot and warm mix asphalt, still result in significant CO₂ emissions (Arnoldussen et al., 2022; Oliveira & Xavier Silva, 2022). Lower-temperature asphalt mixes offer promising emission reductions, with potential savings of up to 30% (Keijzer et al., 2015). One such mix is LEAB (Low Energy Asphalt Concrete), developed by BAM Infra Nederland and now adopted as the standard mix for their projects. LEAB is produced at significantly lower temperatures (110°C compared to the conventional 165°C) while maintaining comparable performance across all layers (base, binder, and surface). In fact, for surface layers, LEAB outperforms traditional asphalt due to slower ageing at lower production temperatures. Additionally, faster cooling allows for earlier reopening of roads (BAM, 2023).

Traditional asphalt production relies on bitumen, a by-product of oil refining with a high environmental footprint, as a binding agent (Oliveira & Xavier Silva, 2022). A more circular approach involves replacing bitumen with bio-based alternatives. One well-studied option is lignin, a by-product of pulp mills and lignocellulosic biorefineries. Replacing 50% of bitumen with lignin could reduce CO₂ emissions by 15–30%, while full replacement could yield reductions of up to 60% in the Dutch asphalt sector (Moretti et al., 2022).

Concrete Paving Blocks

Most concrete paving blocks are made with Ordinary Portland Cement, known for its high performance but also for its environmental cost: the production of 1 tonne of Ordinary Portland Cement emits roughly 1 tonne of CO₂ (Abdila et al., 2025). Therefore, finding sustainable alternatives is urgent. Recently, geopolymer concrete has emerged as a promising substitute, offering benefits in energy conservation, environmental protection, and the reuse of industrial waste (Shehata et al., 2022).

Geopolymers are produced from alumino-silicate-rich materials such as high-calcium fly ash and slag powder. The key advantage lies in their use of alkali-activated binders, which eliminate the need for limestone and the high-temperature kilns required for Ordinary Portland Cement, thus substantially reducing CO₂ emissions. Geopolymer concrete also demonstrates superior thermal and mechanical properties, enhanced durability, and a significantly lower environmental footprint (Yoo et al., 2024).

Despite these advantages, large-scale application of geopolymer concrete still faces hurdles. Variability in industrial by-products affects consistency, while alkaline activators such as sodium hydroxide and sodium silicate raise concerns related to safety and cost. Furthermore, the absence of standardised codes and long-term performance data limits acceptance in practice. Overcoming these barriers through research, standardisation, and field validation is crucial to realise the full potential of geopolymer concrete in circular road construction (Ikotun et al., 2024).

Brick Paving Blocks

Brick paving presents a more complex case. The environmental impact of brick production is primarily due to the combustion of fuels such as natural gas and to CO₂ released from car-

bonate decomposition during the firing process. The three main fuel-related emission stages in brick manufacturing are spray drying, drying, and firing, typically all powered by natural gas. Together, these processes result in 0.15 to 0.2 tonnes of CO₂ emissions per tonne of finished product and require approximately 2.56 GJ of energy per tonne (Besier & Marsidi, 2020).

Given this relatively high carbon footprint, Keijzer et al. (2015) suggest that replacing brick paving with concrete paving blocks could be beneficial from a climate perspective. However, this recommendation is not straightforward. Bricks also offer advantages: their estimated lifespan ranges between 95 and 190 years, which is significantly longer than that of concrete paving blocks (Nusselder et al., 2020). This highlights that substitution decisions must weigh both production emissions and long-term durability, as a material with a higher initial impact may perform better over its full lifecycle.

Although full substitution is debatable, several strategies exist to reduce emissions from brick production. These include fuel substitution (e.g. green gas, hydrogen, electric kilns), use of residual heat, redesign of processes (e.g. more efficient tunnel kilns), and CO₂ capture through post-combustion carbon capture and storage. Lighter product designs can also lower material demand. While drying can be decarbonised in the short term, technologies for low-emission firing are still in development. Implementation is further constrained by long equipment lifespans, grid capacity limitations at remote sites, and the interdependence of drying and firing processes (Besier & Marsidi, 2020). Nonetheless, progress is being made: in 2024, Vandersanden opened the first CO₂-negative brick plant in Lanklaar, combining renewable energy use with CO₂-absorbing production, marking a significant milestone toward climate-neutral brick manufacturing (Redactie Contentmarketing, 2025).

Narrow the loop

Hanemaaijer et al. (2023) define the “Narrow the loop” strategy as reducing the input of raw materials by refusing unnecessary products and using existing ones more efficiently. This section examines how the lifespan of road infrastructure can be extended, thereby delaying the need for large-scale maintenance and material replacement.

For asphalt roads, in-situ rejuvenation is increasingly recognised as a circular maintenance strategy. This preventive surface treatment involves spraying a bitumen-like compound onto the existing pavement to fill micro-cracks, restore aged binder, and reinforce the mortar structure. In the Netherlands, rejuvenation is typically applied every five years, with each application extending service life by approximately two to six years. A common sequence of treatments at the five- and ten-year marks can extend the lifespan by six years in total (Liu et al., 2025). For concrete paving blocks and brick roads, little of such lifespan-extending techniques are documented in literature, highlighting a need for further research into comparable strategies.

In addition to rejuvenation, Chen et al. (2021) describe a broad range of advanced technologies that support preventative road asset management. These include automated defect detection, intelligent construction systems, and predictive maintenance models. Deep learning algorithms can identify and classify surface defects, such as cracks and potholes, using images captured via smartphones, drones, or vehicle-mounted cameras. Subsurface issues, such as debonding or moisture-related damage, can be detected using ground-penetrating radar in combination with neural networks. Time-series forecasting models, such as long short-term memory networks, allow engineers to anticipate degradation based on historical and real-time data. These developments enable earlier and more targeted interventions, reducing the need for premature replacement, but have a very technological nature and are expected to have investment cost.

Slow the loop

Hanemaaijer et al. (2023) define “slowing the loop” as the extension of product and component lifespans through reuse, repair, and remanufacturing. While this may appear similar to

recycling, reuse differs in that it retains the component's original function without breaking it down. Although minor reprocessing may be needed, reuse generally demands significantly less energy than recycling (Iacovidou & Purnell, 2016).

Among circular strategies, reuse stands out as a technically and logistically demanding but environmentally valuable approach. It requires careful specification of reclaimed materials, a functioning reuse market, and additional time and cost compared to straightforward demolition. However, when successful, reuse delivers substantial environmental and financial benefits due to the high embodied energy and long technical lifespan of many materials (Marsh et al., 2022).

This is particularly relevant for tiled paving elements, which often outlast the roads they are installed in. Dutch secondary roads typically have a service life of around 50 years (Keijzer et al., 2015), while paving materials such as concrete blocks and bricks can last up to 75 years and 130–140 years, respectively. This discrepancy highlights the potential for reuse. Current reuse rates support this potential: roughly 80–83% of bricks can be reused (accounting for breakage), and for concrete paving blocks, about 70% remain functionally viable after 50 years (Keijzer et al., 2015; Nusselder et al., 2020). In response, several Dutch municipalities have recently begun to operationalise this potential by establishing storage and reuse hubs where paving elements are temporarily kept for reintegration into future projects (Keuchenius, 2025; Regioedactie Haarlem, 2024; SEB, 2025; Wichgers, 2025).

To support such practices, material passports have recently gained attention. These are digital or physical documentation systems that collect detailed data on the materials used in assets, including composition, source, expected lifespan, and potential reuse pathways (Leindecker et al., 2025). In the context of road infrastructure, material passports offer several benefits. They municipalities to strategically plan maintenance and deconstruction with reuse in mind.

Close the loop

Hanemaaijer et al. (2023) define the “Close the loop” strategy as minimising material losses and undesirable substances, ensuring that only truly unrecoverable waste is incinerated or landfilled. As discussed in the literature review, recycling is already a widespread practice in Dutch road infrastructure. However, this does not necessarily imply that current practices fully align with circular principles. A distinction can be made between open-loop and closed-loop recycling (Iacovidou & Purnell, 2016). In closed-loop systems, materials retain their original quality and function, as is largely the case with asphalt: reclaimed asphalt is reprocessed into new asphalt. In contrast, brick and concrete paving blocks are typically subject to open-loop recycling, in which they are crushed and mixed with other construction and demolition waste. This practice results in quality degradation and loss of functional value. Increasing circularity in these streams requires a shift from open-loop to closed-loop approaches. One way to support this shift is to improve separation at source: rather than mixing different mineral waste types, brick and concrete aggregates should be processed separately to reduce contamination.

This is more feasible for road infrastructure than for buildings, as road pavement demolition waste is more homogenous, mostly consisting of a single material (e.g. asphalt, brick, concrete), while building demolition waste is more heterogenous, consisting of a variety of materials (e.g. concrete, bricks, but also wood, glass, and hazardous materials) (Pallewatta et al., 2023). Separated aggregates can be repurposed in higher-value applications, such as new bricks or prefabricated concrete components. In cases where sufficient purity is ensured, recycled concrete aggregates may even be reused in structural concrete (Zhang et al., 2018).

Appendix B Interview Guide Municipality of Rotterdam

Introductie

Dank u voor uw tijd. Dit interview maakt deel uit van een onderzoek naar de manier waarop de gemeente Rotterdam circulariteit toepast binnen renovatie- en constructieprojecten van wegen. Ik ben met name benieuwd naar uw ervaring met de huidige werkwijzen, uw kijk op circulair werken, en de samenwerking tussen afdelingen.

- Het interview duurt ongeveer 45 minuten.
- Uw antwoorden worden anoniem verwerkt en vertrouwelijk behandeld.
- Mag ik dit gesprek opnemen voor analyse?

1. Achtergrond en functie

- Kunt u uzelf kort voorstellen?
- Wat is uw functie binnen de gemeente Rotterdam?
- Bij welke cluster en/of afdeling bent u werkzaam?
- Hoe bent u betrokken bij renovatie- of constructieprojecten in de openbare ruimte?

2. Huidige werkwijze

- Hoe zou u de huidige aanpak van wegenprojecten omschrijven?
- Wat zijn binnen deze projecten uw verantwoordelijkheden of taken?
- Op welke manier werkt u samen met andere afdelingen of externe partijen?
- Wordt circulariteit momenteel expliciet meegenomen in de werkwijze? Zo ja, hoe?

3. Circulariteit in de praktijk

- In hoeverre speelt circulariteit op dit moment een rol binnen uw projecten of afdeling?
- Kunt u voorbeelden geven van hoe circulair werken wordt toegepast?
- Welke obstakels of knelpunten ervaart u bij het toepassen van circulaire principes?
- Waar ziet u kansen voor verbetering of innovatie op dit gebied?
- Wat heeft u of uw afdeling nodig om circulariteit beter te kunnen toepassen?

4. Reflectie en afsluiting

- Zijn er nog zaken of observaties die u belangrijk vindt met betrekking tot circulariteit of samenwerking binnen de gemeente?
- Heeft u suggesties of aandachtspunten voor het vervolg van dit onderzoek?

Bedankt voor uw tijd en openheid. Ik zal u de resultaten van dit onderzoek toesturen zodra deze beschikbaar zijn.

Appendix C Preparation Site Visits

Guiding Questions

Gemeentelijke context

- Bij welke afdeling bent u werkzaam binnen de gemeente?
- Kunt u iets zeggen over de omvang van uw gemeente (inwonersaantal, areaal openbare ruimte)?
- Wat is de algemene ambitie van uw gemeente op het gebied van circulair werken in de openbare ruimte?

Aanleiding voor het opzetten van de circulaire hub

- Wat was de aanleiding om een circulaire hub voor straatverhardingsmaterialen op te zetten?
- Was er een specifiek project, beleidsdoel of urgentie die dit in gang heeft gezet?
- Wie waren de belangrijkste trekkers van het initiatief (bijv. afdelingen, bestuurders)?
- Tegen welke barrières liep u aan bij de opstart (juridisch, organisatorisch, financieel, technisch)?

Organisatie en werkwijze van de hub

- Welke soorten materialen worden in de hub opgeslagen?
- Hoe komen de materialen binnen bij de hub? (logistiek, registratie, selectie)
- Hoe worden materialen gekoppeld aan nieuwe projecten? (vraag-aanbodproces)
- Hoe lang blijven materialen gemiddeld opgeslagen in de hub?
- Worden materialen ter plaatse bewerkt of verwerkt? Zo ja, op welke manier? (bijv. breken, reinigen, certificeren)

Fysieke inrichting van de hub

- Hoe is de fysieke indeling van de hub vormgegeven? (bijv. gescheiden opslag, indeling per materiaalsoort)
- Hoeveel ruimte is beschikbaar en hoe wordt die benut?
- Is er specifieke infrastructuur aanwezig voor verwerking van materialen? (bijv. breekinstallatie, weegbrug, afwatering)
- Hoe wordt veiligheid en toegankelijkheid op het terrein georganiseerd?

Ervaringen en lessen

- Wat zijn tot nu toe de grootste succesfactoren van de circulaire hub?
- Welke knelpunten of uitdagingen bent u tegengekomen in de praktijk?
- Welke verbeteringen of volgende stappen ziet u voor de toekomst van de hub?

Afsluiting

- Zijn er nog zaken of tips die u wilt meegeven aan andere gemeenten die een vergelijkbare hub willen opzetten?

Consent and Information form for site visits outside of Municipality of Rotterdam

Informatieformulier deelname afstudeeronderzoek MSc Metropolitan Analysis, Design & Engineering

U neemt deel aan een interview in het kader van een afstudeeronderzoek binnen de opleiding Metropolitan Analysis, Design & Engineering (MADE), een gezamenlijke masteropleiding van de Technische Universiteit Delft en Wageningen University & Research.

Dit onderzoek richt zich specifiek op hoe de gemeente Rotterdam de ruimtelijke behoeften voor circulaire stromen van verhardingsmaterialen kan integreren in stedelijke planning. Door in kaart te brengen hoeveel ruimte deze activiteiten vragen, wordt beoogd om beleidskeuzes rondom circulariteit in de openbare ruimte beter te onderbouwen. Daarnaast wordt via interviews met andere gemeenten verkend welke werkwijzen zij hanteren om circulaire initiatieven te faciliteren en welke lessen daaruit te trekken zijn.

Uw deelname aan dit onderzoek is vrijwillig. Tijdens het interview heeft u altijd het recht om:

- Een vraag niet te beantwoorden;
- Het interview op elk moment af te breken zonder opgave van redenen.

De volgende afspraken gelden voor de omgang met uw gegevens:

- Uw persoonsgegevens en antwoorden worden vertrouwelijk behandeld en geanonimiseerd verwerkt.
- Audio-opnames worden alleen gemaakt als u daar expliciet toestemming voor geeft. Deze opnames worden gebruikt voor het uitwerken van een transcript en worden uiterlijk drie maanden na de beoordeling van het afstudeeronderzoek vernietigd.
- Uw persoonsgegevens worden uitsluitend gebruikt voor de doeleinden van dit onderzoek, in overeenstemming met de Algemene Verordening Gegevensbescherming (AVG).
- Uw gegevens worden niet gedeeld met derden zonder uw uitdrukkelijke toestemming.
- Mogelijk worden geanonimiseerde citaten uit uw interview gebruikt in de rapportage; hiervoor wordt apart toestemming gevraagd.

Let op: hoewel er wordt gestreefd naar volledige anonimisering, kan door de context van het onderzoek (bijvoorbeeld het benoemen van specifieke gemeenten) een kleine kans bestaan dat uw antwoorden indirect herleidbaar zijn. Hierover vragen wij apart uw instemming.

Indien u vragen of klachten heeft over het onderzoek, kunt u contact opnemen met de onderzoeker:

Milo Marler,

MSc MADE student

Toestemmingsformulier deelname afstudeeronderzoek MSc Metropolitan Analysis, Design & Engineering

Bij deze verklaar ik:

- Dat ik duidelijk ben ingelicht over het doel en de werkwijze van dit onderzoek.
- Dat ik weet dat mijn deelname vrijwillig is en dat ik op elk moment mag stoppen zonder gevolgen.
- Dat ik begrijp dat mijn persoonsgegevens en antwoorden geanonimiseerd worden verwerkt.
- Dat ik weet dat de gegevens alleen voor dit onderzoek gebruikt worden en niet gedeeld worden met derden zonder mijn toestemming.
- Dat ik weet dat ik toestemming kan geven of weigeren voor het opnemen van het interview en het gebruik van geanonimiseerde citaten.

Toestemmingen:

- Ik geef toestemming voor het opnemen (audio) van het interview.
☐ Ja ☐ Nee
- Ik geef toestemming voor het gebruik van geanonimiseerde citaten uit mijn interview in de eindrapportage.
☐ Ja ☐ Nee
- Ik geef toestemming voor het benoemen en beschrijven van gemeenten in het onderzoek, waarbij mijn antwoorden mogelijk (indirect) herleidbaar zijn.
☐ Ja ☐ Nee

Ik begrijp bovengenoemde zaken en teken hierbij voor mijn deelname aan dit onderzoek.

Gelezen en goedgekeurd te (plaats) op (datum).

Naam + Handtekening student

Naam + Handtekening respondent

.....

.....

Appendix D Policy Document Review

Programme Circular Rotterdam 2023-2026

Building on the strategic direction set in the Environmental Vision, the Programme Circular Rotterdam 2023-2026 provides concrete policy guidance and implementation tools for embedding circularity into practice. Adopted in October 2023, the programme responds to the urgent need to operate within planetary boundaries and reduce reliance on primary resources. The programme translates national ambitions, like the 50% reduction in the use of primary raw materials by 2030 and full circularity by 2050, into local transition agendas tailored to Rotterdam's sectors and stakeholders. These ambitions are operationalized through six transition agendas: three sectoral (construction, organic flows, and consumer goods) and three actor-focused (municipal procurement, businesses, and residents). The construction sector receives particular attention, as it accounts for half of the national raw material use and offers high potential for impactful interventions.

The programme introduces three interrelated strategies. First, it promotes moving “up the R-ladder”, prioritizing reduction, circular design, and reuse over recycling. Second, it adopts a “learning-by-doing” approach: experimenting with pilot projects and using practical insights to refine policy and remove regulatory or procedural barriers. Third, it emphasizes the importance of collaboration throughout the entire material chain, from design and procurement to maintenance and waste processing.

Public space management plays a central role in implementing these strategies. As asset owner and commissioning authority, the municipality has significant influence over how public assets are designed, constructed, maintained, and eventually decommissioned. The programme introduces circular procurement standards and encourages reuse of locally sourced materials, harvested from the city's own demolition and refurbishment projects. Projects like the Claes de Vrieselaan sewer and street renovation serve as pilots for these new approaches.

The programme also outlines key enabling conditions for circularity: spatial facilities (such as material depots), technical tools (such as material passports and digital marketplaces like DuSpot), and financial reforms. It challenges conventional budgeting systems that assume zero end-of-life value, instead advocating for lifecycle-based investment models that retain value across multiple use cycles. By 2026, at least one municipal depot for public space materials is expected to be operational, and 50% of tenders should favour low-environmental-impact materials.

Strategic Asset Management Plan

The Strategic Asset Management Plan, developed by the city maintenance department of the Rotterdam municipality in 2019, outlines a long-term approach to managing public space. Asset management is framed as the next step in optimizing municipal maintenance practices by balancing costs, performance, and risks. Rather than focusing solely on technical conditions, this approach considers the broader societal value of assets and ensures that resources are allocated where they are most needed. Management becomes programmatic and risk-based, aiming to identify both risks and opportunities that can benefit the city.

A key tool within this strategy is the core value model, which assesses risks based on their likelihood and severity. This allows for comparison across different types of risks, from collapsed sewer pipes to malfunctioning parking systems. Once the risk level is known, targeted interventions can be developed to reduce it to an acceptable threshold. Opportunities can be evaluated using the same logic. Six core values guide the assessment of assets: safety, availability, environmental health, quality of the living environment, resilience, and public image. These values reflect a broad ambition: from creating a healthy, liveable, and safe city to ensuring that public space contributes to long-term goals like climate adaptation, circular economy, and energy

transition. Public satisfaction and the city's image are also part of the evaluation framework.

Successful implementation depends on clear organizational conditions, including financial frameworks, information systems, and the skills of municipal professionals. Asset management is thus both a technical methodology and a governance tool to align maintenance with Rotterdam's broader urban development goals. The strategic plan serves as an umbrella for more detailed asset management plans that translate citywide goals into sector-specific actions, for roads, public lighting, green infrastructure, underground utilities, and cultural heritage, among others. These plans include both strategic ambitions and concrete operational measures.

Asset Management Plan Roads

The Asset Management Plan for Roads is one of eleven sectoral plans developed by the Municipality of Rotterdam in 2019. It outlines how road infrastructure management supports the city's strategic goals while serving the needs of its residents. The plan focuses on achieving cost-effective, efficient outcomes through careful asset stewardship.

The municipal road network is divided into three asset groups: pavement structures (e.g., roads, sidewalks, bicycle lanes, and squares), traffic signs (e.g., over 70,000 signs and markings), and street furniture (including 27,000 bicycle stands, 173,000 gullies, and nearly 10,000 benches). Rotterdam distinguishes between arterial roads, which ensure citywide connectivity, and neighborhood-level roads that serve local functions. The paving material is roughly 25% asphalt and concrete, and 75% modular elements. Future transitions favor natural stone, baked bricks, and permeable surfaces to enhance climate resilience and spatial quality.

The city aligns road management with six core public values: safety, availability, environmental health, quality of the urban experience, resilience, and public image. Road safety focuses on eliminating unacceptable risks to users. Availability is ensured through coordinated planning, integrating roadworks with other interventions to minimize disruptions. The strategy emphasizes environmental compliance, noise reduction (using low-noise asphalt), and visual quality through uniform design standards. Climate resilience efforts aim to prevent waterlogging and maintain access during extreme rainfall events.

Rotterdam's road maintenance strategy follows the CROW asset management system. It combines periodic maintenance, corrective maintenance, major maintenance, and replacement, all informed by regular inspections and long-term forecasting:

- Periodic maintenance includes scheduled upkeep like resurfacing or repaving to prevent degradation.
- Corrective maintenance addresses unforeseen damage, such as accidents or subsidence. Critical incidents are resolved within 24 hours via the "Snel Herstel" service teams.
- Major maintenance is applied mid-lifecycle, such as replacing the top layers of asphalt or relaying sidewalks.
- Replacement occurs at the end of an asset's life. For asphalt, the typical lifespan is 45 years; for modular paving, 60 years.

Five primary risk factors guide the road maintenance program: (1) soil settlement, especially problematic in areas with soft subsoil, (2) construction quality, monitored through inspections and contractor performance during warranty periods, (3) aging infrastructure, with replacement needs expected to grow between 2018 and 2039, (4) surface damage like unevenness and raveling, which affects safety and noise performance, and (5) external disruptions, such as heavy traffic or utility failures.

To minimize disruption and maximize investment efficiency, Rotterdam integrates road maintenance with sewer replacement and other infrastructure projects. These combined works reduce street closures and allow for full reconstruction "from façade to façade." Where only sewer replacement occurs, resurfacing is limited to "curb to curb." Material reuse is encouraged, and

natural elevation is restored to original levels. Prioritization is based on subsidence levels and asset age.

Rotterdam Public Space Style Guide

The Rotterdam Public Space Style Guide serves as the principal policy framework for designing and maintaining the city's public spaces. Originally adopted in 2009 and updated in 2024, the handbook outlines clear principles and measures to enhance spatial quality, promote sustainability, and create a unified visual identity. Central to this approach are three core objectives: achieving citywide spatial quality, ensuring that public spaces are maintainable and cost-effective over time, and establishing a common language for collaboration among municipal professionals, external parties, and residents.

The updated 2024 edition responds to emerging societal and environmental challenges. It provides design guidance rooted in three overarching city goals: green and sustainable, inclusive for all, and balanced mobility. These goals are translated into spatial tasks, principles, and design tools across five defining characteristics of Rotterdam's public space: (1) River–Delta–City–Port, (2) Green-blue structure, (3) The Rotterdammer, (4) Modern inner city and boulevards, and (5) Neighbourhood archipelago.

The design principles emphasize greenery, human-centered design, durable and uniform paving materials, and comfortable furniture. A limited palette of robust materials enables easier reuse, coordinated procurement, and greater resistance to vandalism. The Advisory Committee on Public Space (ACOR) reviews deviations, tests, and innovations, while policy updates fall under the Department of Space, Housing and Environment. Through participatory planning processes, residents are actively involved in shaping their neighbourhoods.

Circularity is explicitly embedded within the updated framework, as one of seven key themes under the citywide goal of green and sustainable development. The transition is operationalized under the motto "circular, unless," meaning reuse is prioritized over new materials whenever feasible. The guide refers to other policies like the Assessment Framework for Reuse of Materials in Public Space and material depots support reuse by assessing the technical and environmental suitability of recovered materials. The circularity ladder guides design decisions to optimize reuse, lifespan extension, and low-impact material selection.

In major redevelopment or maintenance projects, the use of materials is evaluated based on lifecycle environmental cost indicators (MKI), which account for production, reuse potential, maintenance cycles, and lifespan within Rotterdam's public realm. Designs are increasingly modular, adaptable, and designed with multiple life cycles in mind. Material passports are used to store data on origin, composition, and reuse options. Circularity efforts also extend to natural flows, such as reusing green waste to improve soil quality. Ongoing experimentation and learning are supported by both the handbook and ACOR, positioning Rotterdam as a city actively piloting circular public space practices.

Rotterdam Public Space Style Toolkit

The Rotterdam Public Space Style Toolkit, updated in 2024, complements the handbook by providing material standards for paving and street furniture. Sidewalks typically use a specific type of concrete tile, while roads are paved with either brick or concrete pavers. The preferred material for each location is defined in the 'klinkerkaart', a map that designates where brick paving is desired and where concrete pavers should be used, ensuring visual consistency. Furniture design is restrained and functional, reflecting Rotterdam's identity as robust, timeless, and elegant. Exceptions to the standard materials are allowed in prominent public spaces such as parks and city squares, provided they are well justified and assessed for their long-term implications.

Assessment Framework for Reuse of Materials in Public Space

The Assessment Framework for Reuse of Materials in Public Space is a policy document developed in late 2024 by Rotterdam's urban development and city management departments. It provides a standardized and transparent method for assessing whether paving materials, specifically concrete pavers, sidewalk tiles, and bricks, can be reused in the context of replacement or redesign projects in public space. The framework supports sustainable material use by promoting circularity and improving consistency in how decisions about reuse are made.

The framework distinguishes four possible reuse pathways: (1) direct reuse of materials in the same function, (2) recycling by the concrete industry to produce high-quality aggregate, (3) reuse in hydraulic engineering, and (4) sale through material marketplaces. Of these, direct reuse is preferred, as it preserves the highest material value and requires the least processing. Recycling by the concrete industry is also encouraged to keep concrete rubble within the supply chain. The third and fourth options are not yet structurally embedded in municipal practice and require further procedural development.

To ensure that reuse becomes standard practice, two conditions must be met. First, the material must be technically and aesthetically suitable for reuse. Second, it must be appropriate for application at the intended location. These aspects need to be addressed in the early stages of project planning, through an on-site pre-selection. The road manager divides the road surface into zones and identifies which parts are suitable for reuse and meet the required standards. These standards focus on three criteria: breakage, surface condition, and contamination. Age is deliberately excluded as a primary factor, since older materials may still be in excellent condition.

Materials deemed promising are transported to a central material depot. At the depot, the stones are cleaned, sorted by machine, and stored, preferably for no more than one year. Concrete pavers are always sent to the depot to be blended with other batches, creating a visually consistent mix suitable for future deployment across various projects. This process helps maintain a coherent aesthetic in the public realm.

Materials that do not meet reuse standards are redirected to alternative reuse routes: they may be recycled into aggregate, used in water engineering works, or offered on reuse marketplaces. At this stage, the framework applies only to the three primary paving types. Other materials can still be considered for reuse, but will need to be assessed separately using the same core criteria.

The environmental and financial implications of reuse are significant. The table below summarizes the environmental impact and cost comparison per square meter between reused and newly produced materials, based on 2023 procurement volumes and operational data from the Reyeroord depot:

Product per m ²	MKI (Reuse)	MKI (New)	Raw Materials (New, kg)	CO ₂ Emissions (New, kg)	Cost (New, €/m ²)	Cost (Reuse, €/m ²)
Concrete pavers	€0.50	€1.70	176 kg	19 kg	€18.50	€9.20
Brick pavers	€0.50	€3.50	168 kg	14 kg	€29.50	€9.20
Sidewalk tiles	€0.50	€0.70	99 kg	8 kg	€13.90	€8.90

All reuse costs include transport, cleaning, and palletization, but not long-term depot storage. These numbers reflect average conditions in 2024, with operations centralized at the Reyeroord facility. This comparison highlights both the ecological benefit and cost-efficiency of reuse. Concrete pavers, for instance, cost nearly twice as much when purchased new. The MKI values,

Room for Reuse

monetized environmental impact scores, also clearly favour reuse, as the additional transport and light processing required have relatively minor impact compared to raw production.

The long-term goal is for nearly all paving in Rotterdam to follow the Rotterdam Public Space Style within 20–25 years. To support this, only a limited number of areas are designated for the use of non-standard materials, typically greener neighbourhoods where aesthetics are shaped more by vegetation than paving. In contrast, heritage areas and high-visibility zones require high-quality brick paving with a warm appearance. These spatial choices are guided by the updated 'klinkerkaart', which defines where brick or concrete paving is preferred and where non-standard reused concrete pavers may still be used, depending on local context such as greenery, building density, and parking pressure.

Appendix E Summaries of Expert Interviews

Expert Interview 1

De Rotterdam, Wilhelminakade 179, April 7, 2025

The interview was conducted with a road asset manager from the Department of Urban Management (Stadsbeheer) in Rotterdam. The interviewee is responsible for the maintenance of paved surfaces in public space and also contributes to the strategic positioning of circular material use within the municipality's broader management and development apparatus.

Asset Management and Lifespan Approach

Road management in Rotterdam follows a strict lifespan-oriented approach. The technical service life of roads is mainly determined by subsurface conditions and linked to the settlement of sewer systems: "We distinguish three age categories: 20, 40, and 60 years. After 20 years, we have about 30 centimeters of subsidence, which means we need to raise the street level." The maintenance cycle is therefore closely aligned with sewer replacement. In roughly 80% of cases, maintenance occurs when the sewer system requires intervention, resulting in integrated replacement projects.

Interdepartmental Collaboration

The degree of collaboration between Urban Management and other municipal departments varies greatly depending on the project type. Large-scale urban transformations are carried out by design teams that include Urban Development and external designers. In these cases, Urban Management primarily assesses feasibility and maintainability: "We are represented in the design team and give input on what we find acceptable or not." For smaller residential street projects, Urban Management leads the process and collaboration is more functional: "They look over your shoulder a bit, or they have some requests, green sections, parking spaces laid out slightly differently."

Material Development and Circular Application

The municipality develops new materials that align with the aesthetics of the Rotterdamse Stijl while improving environmental performance. Examples include concrete pavers designed to resemble brick and new granitic tiles: "We have a concrete paver that looks like a brick. We developed that together some years ago." At the same time, planned maintenance projects aim to reuse existing materials. This proves challenging due to the lack of standardisation before 1996: "There was no central procurement then. One batch was eight centimeters thick, another 8.5. That makes reuse difficult."

Logistical Constraints and Outsourcing

One of the largest structural barriers is the lack of space for storing, sorting, and cleaning materials. Initiatives such as the depot in Reyerwaard are promising but small-scale: "You get all different sizes and thicknesses [...] You shouldn't have reused that." According to the interviewee, outsourcing storage and sorting to private contractors would be a logical next step: "You would put out a tender. They can clean, package, palletise, and deliver the materials when we need them."

Design Choices and Aesthetics

There is experimentation with visually appealing combinations of reused paving stones, which designers describe as creating a "patchwork effect": "It looks good, but making that kind of mix is incredibly difficult. It takes up huge amounts of space." Proper execution would require separated storage and precise registration systems, something the municipality currently lacks.

Policy Anchoring and Organisational Tensions

Although the importance of circular working is widely acknowledged, structural anchoring remains limited. There is an ambition to embed circularity into project scope forms, digital planning systems, and technical specifications: "We make scope forms as the first step in the chain. We want to include what materials are released and the potential for reuse." At the same time,

the interviewee emphasised that this cannot succeed without dedicated personnel: “You need people to do it, to inspect the stones, maintain registration, and manage depots.” Without central coordination, circular practice remains highly dependent on individual motivation and ad hoc initiatives.

Expert Interview 2

Department of Material Supply, Melanchtonweg 125, April 14, 2025

This interview was conducted with a senior advisor from the Material Supply division within the Urban Management (Stadsbeheer) cluster of the Municipality of Rotterdam. The interviewee is responsible for quality control of new and reused paving materials, drafting technical requirements in tenders, and matching released materials with new applications.

Collaboration within the Municipal Organisation

Material Supply works closely with asset managers, designers, and project supervisors. The interviewee acts as a connecting link: “When I hear that materials are being released somewhere, I also check whether other projects might need materials.” Through regular meetings in professional working groups and during project preparation, reuse is being embedded increasingly early in the process. For each project, the asset manager determines which materials are suitable for reuse, after which Material Supply handles processing and storage. Collaboration with the engineering office of the Urban Development department is also crucial in this process.

Logistics and Storage

The focus lies on three main material types: concrete paving blocks, concrete tiles, and fired bricks. Materials can only be added to the municipal stock if they meet strict requirements: “We only accept materials that are palletised and packaged as if they were new.” These conditions are now standard in tender specifications and are enforced by site supervisors. Within these material streams, carriageways are more suitable for reuse than sidewalks. Carriageways are generally cleaner and less damaged because they receive more frequent maintenance and are resurfaced sooner: “Stones from carriageways are often quite clean and intact. Sidewalk stones are more likely to have paint or dirt on them, or be damaged.” As a result, the reuse yield from carriageways is usually higher. The central circular depot is located at Bunschotenweg in Rotterdam-South and has approximately 700 m² of paved surface. Only part of this is currently suitable for storage; expansion is needed but constrained by vegetation and uncertainty over land-use rights: “It’s rented for now [...] but the zoning is still unclear.” The municipality is exploring additional locations across the city to enable distribution and reduce transport distances.

Quality Assessment Using the Evaluation Framework

The internal evaluation framework, developed by a municipal working group, is now in use. Asset managers assess streets at the material level according to criteria such as damage, type, and visual quality: “Managers divide a street into different sections. Each section is then assessed: how much of it is still reusable?” Only approved materials are cleaned, formatted, and palletised by the contractor. In some cases, rejected materials are temporarily reused—for instance, in parking areas: “Those would have been rejected by the framework but were still requested for temporary paving.”

Administrative and Digital Challenges

Processing reused materials has not yet been fully institutionalised. Orders are still managed via a separate Excel list, and purchasing through the regular municipal procurement app is not yet possible: “We want to reach a point where reused materials can be ordered just like new materials.” To that end, new product codes are currently being developed.

Cultural and Organisational Challenges

Although the system is technically well set up, cultural and organisational barriers persist. Some project supervisors still prefer to use new materials. Oversight can also be lost when ma-

materials are stored outside official depots: “Sometimes supervisors exchange materials among themselves without informing us, so we can’t keep track.” Nevertheless, support for circular practices is growing: “I notice that many people understand that materials shouldn’t just be discarded. So I’m optimistic that it will work out.”

Expert Interview 3

De Rotterdam, Wilhelminakade 179, April 15, 2025

This interview was conducted with a circularity advisor at the Urban Management (Stadsbeheer) department of the Municipality of Rotterdam. The interviewee is involved in implementing circular objectives in public space management, with a particular focus on paving materials.

Strategic Focus and Material Flows

The municipality purchases approximately 60 to 70 million kilograms of concrete products annually, mainly paving stones and tiles. Since paving materials account for around 70% of the CO₂ emissions associated with outdoor space procurement, policy efforts concentrate on this category. The main objective is to reduce unnecessary procurement by organising smarter reuse: “We purchase about six million stones and 2.5 million tiles each year. [...] Concrete is by far the largest stream.” Within this category, concrete paving blocks are most commonly used. For clay bricks and natural stone, aesthetic or volume-related constraints are more frequent. Within these material flows, carriageways are more suitable for reuse than sidewalks, both technically and aesthetically: “There’s more potential in carriageways. Sidewalks show more wear and dirt, and residents tend to be more critical.” Sidewalk tiles lose visual quality more quickly through chewing gum, oil, or paint stains, leading to the perception that they are unusable, even when they remain functionally sound.

Depot Strategy and Spatial Challenges

The municipality is exploring how to structure circular depots more systematically. The current site at Bunschotenweg has limited usability: parts are overgrown or unpaved, and the legal right of use is uncertain due to previous commitments to the local community. Investments in full paving (approximately €800,000) are only justified if the site can be used for at least ten years: “There was a commitment to green the area. [...] That makes it complicated to turn it into a depot now.” To make large-scale reuse operationally viable, roughly one hectare of storage area is needed, ideally distributed across three strategically located depots. Too many small sites are undesirable due to management and staffing costs. Each site should also be easily accessible for heavy vehicles.

Working Methods and Standardisation

New procedures have been developed to integrate reuse into existing project workflows. Contractors are required to clean materials of sand and sludge on-site, palletise them, and wrap them in foil so that they are identical in presentation to new materials: “The idea is that it looks exactly like a new package.” For concrete paving stones, mixed pallets are often made, requiring additional sorting and processing at dedicated facilities such as the site in Reyerood. Within regular maintenance projects, reuse is already the standard practice. However, in larger transformations, such as sewer replacement, new materials are still preferred, partly due to the technical condition of older materials but also because of the desire to offer residents something visibly “new.” Pilot projects are now testing how reuse can become the default even in these contexts.

Ownership and Procurement

Material ownership formally remains with the municipality, even when operations are outsourced. Depot management and cleaning are sometimes contracted out through tenders: “You could tender depot management, but I’m not in favour of that, you lose control.” For new materials, tenders now require partial use of recycled content, particularly in concrete. For clay bricks, this remains more difficult due to aesthetic requirements.

Organisation and Internal Integration

Implementing circular practices does not require new technologies but rather a redesign of organisational processes and responsibilities: “Reusing a tile isn’t difficult. Organising it properly within such a large organisation, that’s the challenge.” The process must be adjusted across all stages, from material assessment and tender formulation to logistics, administration, and financial accounting.

Resistance and Organisational Culture

Although practice shows that reuse is on average five euros per square metre cheaper than new material, persistent biases remain within the organisation. Some designers and project managers still prefer new materials, out of habit or aesthetic preference: “There’s a bit of cold feet. [...] But residents usually respond very reasonably, if it’s laid properly, they don’t mind.”

Expert Interview 4

De Rotterdam, Wilhelminakade 179, April 16, 2025

This interview was conducted with a road construction advisor from the Engineering Department of the Municipality of Rotterdam. The interviewee specialises in pavements and foundation structures within the upper 1.5 metres of road construction.

Division of Roles and Commissioning Structure

The Engineering Department operates on behalf of both Urban Management (Stadsbeheer), for maintenance projects, and Urban Development (Stadsontwikkeling), for redesign and transformation projects. For maintenance projects, the advisor is often involved in assessing the quality of existing materials, while in development projects the focus lies on design and construction. In both contexts, the advisor provides recommendations on material application, reuse potential, and foundation composition. Mixed aggregate, a blend of crushed concrete and masonry, is standardly applied as a foundation layer beneath new pavements.

Assessment and Classification of Reusable Material

The municipality employs a visual classification system (classes A through D or E) to assess the reusability of paving materials such as concrete paving stones, kerbstones, and sidewalk tiles. Official NEN standards for reused materials do not yet exist; classification is therefore based on visible damage indicators such as chipped corners, cracks, or surface weathering: “We haven’t formulated requirements in percentages; visual criteria are leading.” When reusability is uncertain, materials are sometimes flipped or included in mixed pallets to extend their usability. Carriageways generally yield better-quality materials for reuse than sidewalks, as they are less affected by aesthetic wear: “Sidewalks are more prone to chewing gum, oil, paint, or surface degradation, while carriageways remain technically in better condition.” Consequently, reuse from carriageways is often more efficient, provided that the subbase and underlying layers are also suitable.

Intermediate Depots and Logistical Constraints

A persistent challenge is the lack of intermediate depots. Without temporary storage and inspection sites, organising local reuse remains difficult: “I’ve been saying this for years, we can reuse the materials, but we need a place to put them.” Due to the absence of suitable storage, materials are frequently sent to crushing facilities, even when local reuse would be technically possible.

Processing Through Crushing Facilities

The municipality maintains long-term contracts with regional crushing companies. Released materials such as clean concrete rubble, masonry rubble, and mixed aggregates are routinely transported there and later repurchased as certified foundation material. These contracts stipulate that suppliers must maintain a minimum stock to ensure availability during emergencies.

Role of the Circular Materials Bank

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The Circular Materials Bank manages material flows within the municipality and coordinates administrative and logistical processes between projects. The CMB oversees transport documentation, environmental certificates, and facilitates the direct transfer of released materials from project A to project B wherever possible. The interviewee, as a road construction specialist, was added to strengthen the link between the CMB and aboveground pavement materials.

Regional Reuse of Asphalt

Asphalt has been regionally reused for decades. Up to 65% recycled asphalt is applied in base layers, and approximately 30% in surface layers. Due to technical requirements such as temperature control and curing, local reuse of asphalt within Rotterdam is not feasible. Depending on the contractor, asphalt is transported to the affiliated regional asphalt plant for recycling.

Secondary Use of Non-Reusable Elements

Concrete paving stones and tiles that are no longer suitable for road surfaces are sometimes reused in hydraulic engineering projects as filling or reinforcement material, for example, in the Maashaven area. A separate depot at Radiostraat has been designated for this purpose: "If it's no longer good enough for the street, it can still serve perfectly well at the bottom of a harbour." The interviewee emphasised that while technical reuse is feasible, structural embedding is still lacking. Without standardised procedures, storage infrastructure, and clear administrative responsibility, circular initiatives remain ad hoc and dependent on individual effort: "As long as you don't have a location, a process, or someone to open the gate, it all stays voluntary."

Expert Interview 5

Microsoft Teams, May 1, 2025

The interview was conducted with a landscape designer from the Spatial Planning, Housing, and Environment (Ruimte, Wonen en Milieu, RWM) team of the Urban Development Department. The interviewee is responsible for developing policy-based design guidelines for public space, including street profiles, street furniture, paving materials, and the city's standardisation policy.

Policy Design Role and Standardisation

The interviewee's role involves developing urban standards, such as furniture and paving materials, that are subsequently implemented citywide through documents like the Toolkit Rotterdamse Stijl: "We don't design a specific street or square, that's what area designers at ROA do. What we create are generic design frameworks and policies for the whole city." New designs, such as benches or paving elements, are first tested in pilot projects, evaluated, and then formalised into standard policy.

Deviations through the ACOR

The Advisory Committee for Public Space (ACOR) reviews requests to deviate from established design policies. In practice, its recommendations carry significant weight: "In principle it's advisory, but since the members are quite high in the hierarchy, their advice is effectively decisive." Most requests concern the use of alternative paving materials, such as clay bricks instead of concrete, or expressive forms of street communication like engraved tiles or signage.

Role in Large-Scale Maintenance Projects

Large-scale sewer replacement projects almost always entail a full redesign of the street. This opens opportunities to adjust parking, drainage, and greening. While area designers from ROA lead the design process, the Urban Development Department remains involved through its policy frameworks: "When the sewers are replaced, the whole street is opened up. That creates both freedom and an obligation to reconsider the design."

Limited Role of Circularity in Design Practice

Circularity currently plays only a marginal role in above-ground design practice. Below ground, sand is relatively circular, but additional material is always required due to subsidence: "That sand stays sand, they put some aside, but you always end up needing more." Above ground,

nearly all elements are replaced, even when some materials are still technically sound: “The standard procedure is simply to remove everything.”

Barriers: Standardisation and Innovation

New circular materials often fail to align with existing standards: “What I see happening a lot is that innovations are deliberately made different. You get a stone made from harbour sludge, nice idea, but it doesn’t fit in terms of size or strength.” According to the interviewee, this is a fundamental barrier to reuse and the integration of innovations: “As soon as you allow new dimensions or forms, standardisation becomes unsustainable and interchangeability disappears.” They argue that successful innovation must stay within existing dimensions, colours, and strength classes. Standardisation, in their view, is the key to successful circularity: “Circular working basically means not reinventing everything each time.” Only innovations that are technically and aesthetically identical to the current standard can be implemented without resistance.

Depot Space as a Planning Constraint

Although physical space exists, it is rarely reserved for circular hubs in spatial planning: “I don’t believe for a second that there’s no space, it’s just that something else always takes priority.” The interviewee questions whether circular depots necessarily need to be located within city limits: “Our paving comes from all over the Netherlands, so why should circular material have to be reused within 500 metres?”

Appendix F Full overview of material inflows and outflows

MATERIAL	STOCK (m2)	DEMAND (m2)
SBS-RS	240153,75	979789,35
BSS-RS GR	147259,9619	438212,6167
BSS-RS WB	10429,33333	157572,3333
BSS non-RS	1212434,719	514635,7857
ASPHALT	479932,3214	0
TOTAL	2090210,086	2090210,086

Appendix G Total Material Flows Including Reusable Share

Under Realistic Reuse Rates

MATERIAL	STOCK (m2)	INBUD (m2)	REUSABLE (m2)	NEW (m2)	DEMAND (m2)
SBS-RS	240153,75	99937,72583	140216,0242	839573,3258	979789,35
BSS-RS GR	147259,9619	48367,51074	98892,45116	339320,1655	438212,6167
BSS-RS WB	10429,33333	3349,014667	7080,318667	150492,0147	157572,3333
BSS non-RS	1212434,719	639471,9148	572962,8043	0	514635,7857
BSS non-RS 1	59837,58333	27285,938	32551,64533	0	0
BSS non-RS 2	266243,7857	126273,4095	139970,3762	0	0
BSS non-RS 3	550293,5833	281322,5617	268971,0216	0	0
BSS non-RS 4	285530,7167	170059,9375	115470,7791	0	0
BSS non-RS 5	42045,13333	26046,15136	15998,98197	0	0
BSS non-RS 6	8483,916667	8483,916667	0	0	0
ASPHALT	479932,3214	479932,3214	0	0	0
TOTAL	2090210,086	1271058,487	819151,5983	1329385,506	2090210,086

Under Theoretic Reuse Rates

MATERIAL	STOCK (m2)	INBUD (m2)	REUSABLE (m2)	NEW (m2)	DEMAND (m2)
SBS-RS	240153,75	48030,75	192123	787666,35	979789,35
BSS-RS GR	147259,9619	30877,34171	116382,6202	321829,9965	438212,6167
BSS-RS WB	10429,33333	2085,866667	8343,466667	149228,8667	157572,3333
BSS non-RS	1212434,719	538409,3437	674025,3754	0	514635,7857
BSS non-RS 1	59837,58333	21541,53	38296,05333	0	0
BSS non-RS 2	266243,7857	101621,2669	164622,5189	0	0
BSS non-RS 3	550293,5833	233857,0873	316436,496	0	0
BSS non-RS 4	285530,7167	149682,7412	135847,9755	0	0
BSS non-RS 5	42045,13333	23222,8016	18822,33173	0	0
BSS non-RS 6	8483,916667	8483,916667	0	0	0
ASPHALT	479932,3214	479932,3214	0	0	0
TOTAL	2090210,086	1099335,623	990874,4622	1258725,213	2090210,086

Appendix H Summaries of Site Visits

Site Visit Apeldoorn

The visit involved discussions with a municipal circularity advisor and the manager of the circular yard.

Motivation for the Circular Yard

The circular yard was initiated to improve handling of materials released from public space projects. What started as a storage site for one district evolved into a central hub for the entire city. Previously, materials were stored in scattered locations, causing inefficiencies and lack of oversight. The hub did not originate from a formal policy directive but from practical initiative at the operational level. Frontline staff began collecting, sorting, and documenting reusable materials. Political support followed later, when aldermen recognized the initiative's value and allowed it to continue.

Operations at the Yard

Stored materials include concrete and clay paving blocks, slabs, curbstones, street furniture, special elements, sewerage components, and green waste. Formally, storage is limited to one year, but in practice this is applied flexibly: promising materials stay longer, while low-value materials leave quickly. Popular items such as 30x30 cm paving slabs are reused frequently, while irregular pieces are rarely accepted. Intake agreements exist but are inconsistently applied; materials often arrive unannounced. Registration is partly managed through the DuSpot platform, although communication remains largely informal. Ideally, reuse follows three steps: within the same project, directly to another project via DuSpot, and only then through interim storage at the yard. In practice, exchanges between projects are difficult to coordinate. Over time, stricter criteria were applied for acceptance, with unusable materials immediately removed.

Circularity still depends on the willingness of individual project teams. Without prioritization by internal clients, no mandate or budget exists to enforce reuse. Furthermore, legal and organizational frameworks for material exchange, especially with market parties or other governments, are missing. The absence of formal policy remains a recurring obstacle.

Physical Layout

The temporary yard covers roughly 3,000 m², divided into zones for paving materials, street furniture, special elements, and green waste. No processing takes place; materials are only collected, sorted, palletized, and occasionally cleaned. The new site will expand to 4,000 m² and include a clear separation between daily maintenance operations and the circular yard, physically divided by fencing. Space allocation is based on estimated material volumes but is difficult to predict, as unique elements occupy disproportionate amounts of space. Experience shows that the yard often reaches full capacity. A materials atlas and passports per district are under development to provide better insight into flows. However, diversity in design across districts complicates standardization and reuse. From 2027 onward, a municipal yard in the southern district will be partially transformed into a circular yard when other services vacate the site.

Experiences and Lessons

Reused materials have been successfully applied in squares, parking areas, and street furniture. Yet progress relies heavily on individual commitment, available space, time, and communication. Persistent challenges include lack of central steering, limited use of DuSpot, space constraints, inefficient stock management, and limited staff capacity. Tensions also exist between efficiency and circularity, as contractors often prefer new, undamaged materials.

Circular working is compared to the introduction of ecological verge management: initial resistance, gradual adaptation, and eventual acceptance. Clear guidelines and visible success stories are seen as essential to accelerate this transition. The municipality is working toward

structural embedding through assessment frameworks and design guidelines, but circularity remains a process of experimentation constrained by practical limitations.

Site Visit Haarlem

The visit was guided by the municipality's senior process manager and sustainability coordinator for civil works. The hub opened at the end of last year and has been fully operational since early this year, providing storage and reuse facilities for materials from the public space.

Preparation

The development of the hub took more than a year and a half. Finding a suitable location proved difficult. An initial attempt to establish the hub on municipal land failed due to the limited availability of the intended site. Eventually, a plot in the Waarderpolder industrial area became available. This location was highly suitable thanks to existing facilities, such as a weighbridge, from its former use as a demolition company's storage yard. Because the site became available unexpectedly, the full financing could not be arranged in advance. As a result, the hub was initially financed through budgets of several public space projects, while work is ongoing to establish it as an independent project.

Operation of the Hub

The hub covers 7,200 m², with capacity for approximately 10,000 m² of materials. By late May, around 4,000 m² was in use. The site was set up using mostly circular materials, with only the asphalt top layer being newly applied. Stored items include concrete elements, paving materials, manholes, traffic lights, and bicycle racks.

The site is more than just a storage facility. It also accommodates parking, charging for electric vehicles and construction machinery, and processing of timber from felled city trees. This wood is dried, sawn, and sold directly from the site.

Management of the hub is outsourced to a transport company responsible for sorting and preparing materials for reuse in new projects. The site is intended for construction companies working on municipal contracts and is not open to the general public. Three fixed construction partners jointly own the hub under a framework contract lasting eight years, with options for two extensions.

A digital registration system, developed by one of the contractors, records the materials stored on-site. Two municipal engineering consultancies actively use this system when designing roads and public space elements, checking for materials available for reuse.

Reuse of Paving Materials

Sidewalk tiles are delivered stacked on pallets, while clay and concrete pavers are delivered loose from projects across the city. At the hub, they are cleaned with high-pressure water or air, depending on technical requirements. They are then palletized using mobile equipment, allowing them to be relaid mechanically. Pallets are wrapped in plastic and stored in stacks—up to three layers for pavers and four for sidewalk tiles.

Clay pavers are particularly popular due to their long lifespan of up to 180 years. Concrete pavers and sidewalk tiles, when reused, are more hardened than at first installation and thus less prone to breakage. Although technical lifespans are not monitored systematically, from an asset management perspective the expectation is that materials should last at least another forty years, corresponding to the next major maintenance cycle. This assessment is based primarily on physical inspection, relying on the look and feel of the stones. If unsuitable for heavily trafficked areas, materials can still be applied in less demanding locations, such as parking lots or sidewalks.

The storage period at the hub is limited to a maximum of two years. If no project is found within that time, materials are listed for reuse outside the municipality via DuSpot, a public materials matching platform, or through contractors' networks. Space limitations require careful selec-

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tion of what is stored. Not all materials are equally in demand. Special elements that fit only specific sites are difficult to redeploy and are only stored if a destination within two years is known. Larger objects such as bicycle racks are highly reusable but occupy significant space, requiring flexible management.

Appendix I Explanation Spatial Requirements

Spatial Requirements for On-Site Material Storage

Paving materials are typically stored on pallets to allow for easier handling, stacking, and inventory management. The most commonly used pallet type is the EPAL Euro pallet, which has a standard surface area of 0.96 m² (EPAL Worldwide, n.d.). Based on site visits and expert interviews, it was found that a single pallet can hold approximately 10 m² of paving elements. The same applies to secondary paving materials, although stacking practices vary depending on how well the pallets are loaded and sealed. At the circular construction hub in Haarlem, bricks and concrete paving blocks were observed to be stacked three layers high when tightly sealed, whereas at the storage hub in Apeldoorn stacking was typically limited to two layers. This difference was mainly due to irregular palletisation and less uniform packaging of the materials, which reduced stability and overall storage efficiency.

Spatial Requirements for On-Site Logistics

Observations from the site visits in Apeldoorn and Haarlem show that on-site logistics for circular material hubs are shaped by two main operational needs: the circulation space between stored materials, and the loading and unloading of incoming and outgoing materials.

A key aspect of internal circulation is aisle allowance, the proportion of the total operational area allocated to equipment, material handling, and personnel movement (Tompkins et al., 2010). For large and heavy unit loads, an allowance of 30 - 40% is recommended; the upper bound is applied here due to the weight of paving materials and the use of heavy handling equipment in outdoor depots. This means that only 60% of the gross storage area can be used for net storage. The gross storage area is calculated by dividing the surface area of the stacked pallets, as determined in the previous section, by a factor of 0.6. For example, if 1,000 m² of net storage is needed, the total gross area required would be approximately 1,667 m².

Loading and unloading areas require additional space. There is no central Dutch standard that prescribes the exact width or length of loading bays. However, practical design guidelines suggest that the manoeuvring area should be at least twice the length of the largest truck in order to ensure safe entry and exit (DockEquipment.eu, 2015). For a standard truck of approximately with a length of 12 - 18.75 m and a width of 2.55 m (RDW, 2025), this translates into a required manoeuvring distance of about 24 - 37.5 m, combined with a minimum clear width of around 3.5 m to accommodate the vehicle and necessary clearance margins. This results in a rectangular manoeuvring envelope of roughly 84 - 131.25 m². To guarantee operational flexibility and account for safety margins, a total surface area of approximately 150 m² can be considered a reasonable design assumption for accommodating a standard truck during loading and unloading operations.

The Circular Construction Hub in Haarlem included a dedicated zone for mechanically palletising secondary paving materials. This process was carried out with mobile equipment that requires only a small fixed footprint. The main spatial requirement arises from the loose paving blocks awaiting palletisation, which are often stored in large piles prior to processing. No specific design guidelines or sources were found that prescribe spatial standards for such operations. To allow sufficient working area for both the equipment and safe material handling, an allocation of approximately 200 m² is therefore taken as a generous design estimate.

Spatial Requirements for On-Site Additional Functions

In addition to storage and logistics, circular material hubs often require dedicated space for supporting activities that enable day-to-day operations. Examples include office space for hub staff, parking areas for visitors or contractors, and designated zones for preparing secondary materials, where the palletising, sorting, or packaging of paving materials before redistribution takes place.

Site visits showed that hub operations require indoor space for staff to perform administrative tasks, hold meetings, receive visitors, and take breaks. In both Apeldoorn and Haarlem, this was not provided through permanent buildings but through temporary site offices, commonly referred to as portable cabins. These are prefabricated modular units that can be relocated or repurposed once no longer needed on-site. Their dimensions are comparable to standard shipping containers, typically around 6 m in length and 2.5 m in width (CBOX, n.d.). Assuming two such units are used to accommodate office space, seating areas, washrooms, and a kitchenette, this amounts to approximately 30 m². To account for additional space requirements for utilities such as water and power connections, a total area of 50 m² is considered a reasonable estimate.

Parking space for visitors and contractors is another common requirement. Based on site visits, around five parking spaces would suffice, located close to the main entrance to facilitate short-term access. Standard passenger vehicle parking spaces are regulated through NEN-2443 and measure approximately 2.5 m in width and 5.0 m in length, resulting in 12.5 m² per space (CROW, 2012). When circulation and turning space are included, a total allocation of around 20–25 m² per space is recommended. Additional area is also needed for bicycle parking to accommodate staff and visitors arriving by bike. To ensure sufficient flexibility and account for variation in layout, the combined total for five car spaces and a small bicycle rack is set at approximately 150 m².

Spatial Requirements for Site Selection

Site selection for these types of facilities is particularly challenging, as in the Netherlands the concept of milieucategorie (environmental zoning) is applied. This system classifies business activities into categories based on their environmental impact, ranging from functiemenging (functional mix) and categories 1–2, which include functions compatible with residential areas, to category 4 and the industrieterrein (Industrial Area) classification, which include the heaviest industrial activities such as oil refineries, asphalt plants, or nuclear power plants (VNG, 2024).

For circular storage hubs focused solely on storage and redistribution, an environmental zoning category of 2 is sufficient, as these activities are comparable to light industrial functions with limited environmental nuisance, such as supermarkets. In contrast, circular construction hubs that also include processing activities, such as mechanical palletising or cleaning, require categories 4.1 or higher, as they generate more noise and emissions and therefore need greater separation distances from sensitive land uses such as housing (Tsui et al., 2024).

Appendix J Overview of Annual Modular Paving Flows

Under Realistic Reuse Rates

SBS-RS

STATE	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038
STOCK	29843,72778	26532,38611	31804,40278	32948,40278	27649,82897	27332,08452	22500,77341	15338,85675	10547,19008	8787,565079	2457,865079	2325,555556	1042,555556	1042,555556
INBUD	12447,20361	12082,46269	14072,37103	13981,70482	11487,82743	11049,08493	9209,911824	5870,277657	3923,829324	3131,998074	920,1980736	860,6587879	450,0987879	450,0987879
REUSABLE	17396,52417	14449,92342	17732,03175	18966,69796	16162,00153	16282,99959	13290,86159	9468,579089	6623,360756	5655,567006	1537,667006	1464,896768	592,4567677	592,4567677
NEW	112501,2314	114633,2071	138965,5488	121429,2311	93417,42513	55185,45485	64878,37063	44345,36979	29453,33813	26870,75688	14355,32354	13644,37949	5958,219495	3935,469495
DEMAND	129897,7556	129083,1306	156697,5806	140395,929	109579,4267	71468,45444	78169,23222	53813,94888	36076,69888	32526,32388	15892,99055	15109,27626	6550,676263	4527,926263

BSS-RS GR

MATERIAL	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038
STOCK	11920,25635	17027,99444	17646,14444	27392,76566	22889,68232	35142,84899	5308,987879	3203,854545	2521,354545	2505,854545	601,8545455	409,8545455	344,2545455	344,2545455
INBUD	3904,392765	5660,425756	5845,408956	8918,82441	7543,862343	11453,96168	1794,057988	1040,270521	820,2158545	815,2558545	205,9758545	144,5358545	110,1614545	110,1614545
REUSABLE	8015,863584	11367,56869	11800,73549	18473,94125	15345,81998	23688,88731	3514,929891	2163,584024	1701,138691	1690,598691	395,8786909	265,3186909	234,0930909	234,0930909
NEW	30500,79955	59184,42778	47646,74431	39153,88704	39195,46068	17964,06002	22294,95633	15771,5522	16036,49753	14815,25975	16109,97975	6861,363127	6892,588727	6892,588727
DEMAND	38516,66313	70551,99646	59447,4798	57627,82828	54541,28066	41652,94733	25809,88622	17935,13622	17737,63622	16505,85844	16505,85844	7126,681818	7126,681818	7126,681818

BSS-RS WB

MATERIAL	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038
STOCK	5635,833333	1724,333333	734,4166667	258,25	1655,25	319,5833333	20,33333333	20,33333333	20,33333333	20,33333333	20,33333333	0	0	0
INBUD	1803,466667	551,7866667	237,9203333	85,547	532,587	105,1736667	6,506666667	6,506666667	6,506666667	6,506666667	6,506666667	0	0	0
REUSABLE	3832,366667	1172,546667	496,4963333	172,703	1122,663	214,4096667	13,82666667	13,82666667	13,82666667	13,82666667	13,82666667	0	0	0
NEW	13461,41111	18641,56444	21135,03144	34620,15811	26657,36478	22016,78478	2853,34	2322,34	2066,34	2066,34	4651,34	0	0	0
DEMAND	17293,77778	19814,11111	21631,52778	34792,86111	27780,02778	22231,19444	2867,166667	2336,166667	2080,166667	2080,166667	4665,166667	0	0	0

BSS non-RS

MATERIAL	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038
STOCK 1	5752,666667	5815,008333	6818,391667	6734,831061	7765,014394	18577,36439	1902,147727	1387,597727	1387,597727	1307,472727	708,8727273	708,8727273	708,8727273	262,8727273
STOCK 2	26469,41198	25810,74293	38911,74293	36755,52323	36065,66133	27090,57799	19646,79466	19239,24466	9983,411328	9715,63355	7388,050216	4540,463636	2313,263636	2313,263636
STOCK 3	38009,98232	56669,04899	75127,13232	87094,90505	83471,20267	63116,24434	35203,97767	30961,49434	21607,911	21365,46656	16205,04989	9658,414394	6336,814394	5465,939394
STOCK 4	24269,34444	25856,30278	46789,93611	45132,17096	44723,92096	38640,07652	21381,9654	16191,43207	11604,7654	10340,6404	150,040404	150,040404	150,040404	150,040404
STOCK 5	5216,233333	5234,566667	4549,583333	9070,666667	5758,333333	8478,5	2995,916667	702,6666667	17,33333333	17,33333333	1	1	1	1
STOCK 6	1331,638889	1101,138889	1168,138889	1100,305556	1123,638889	1444,305556	686,6666667	283,9166667	122,0833333	122,0833333	0	0	0	0
INBUD 1	2623,216	2651,6438	3109,1866	3071,082964	3540,846564	8471,278164	867,3793636	632,7445636	632,7445636	596,2075636	323,2459636	323,2459636	323,2459636	119,8699636
INBUD 2	12401,14839	12276,05398	18368,66118	17299,8505	16999,83454	12617,46214	9418,148135	9384,309815	4851,747415	4715,442348	3527,443815	2228,944335	1092,181455	1092,181455
INBUD 3	19400,29498	28923,8826	38344,88834	44453,23954	42603,70184	32644,39991	17990,9582	15802,74671	11028,67778	10904,93413	8271,057465	4929,654707	3234,310067	2789,815467
INBUD 4	13077,16763	14871,84103	26633,75223	26829,54138	27627,38018	23860,2637	13174,0413	10025,73474	7185,670738	6402,924538	92,90501818	92,90501818	92,90501818	92,90501818
INBUD 5	3233,826613	3245,178613	2821,036933	5616,5568	3565,56	5249,8872	1855,0716	435,0912	10,7328	10,7328	0,6192	0,6192	0,6192	0,6192
INBUD 6	1331,638889	1101,138889	1168,138889	1100,305556	1123,638889	1444,305556	686,6666667	283,9166667	122,0833333	122,0833333	0	0	0	0
REUSABLE 1	3129,450667	3163,364533	3709,205067	3663,748097	4224,16783	10106,08623	1034,768364	754,8531636	754,8531636	711,2651636	385,6267636	385,6267636	385,6267636	143,0027636
REUSABLE 2	14068,26358	13534,68895	20543,08175	19455,67274	19065,82679	14473,11586	10228,64653	9854,934846	5131,663912	5000,191201	3860,606401	2311,519302	1221,082182	1221,082182
REUSABLE 3	18609,68735	27745,16639	36782,24399	42641,66551	40867,50083	30471,84443	17213,01947	15158,74763	10579,23323	10460,53243	7933,992427	4728,759687	3102,504327	2676,123927
REUSABLE 4	11192,17682	10984,46175	20156,18388	18302,62958	17096,54078	14779,81282	8207,924106	6165,697333	4419,094666	3937,715866	57,13538586	57,13538586	57,13538586	57,13538586
REUSABLE 5	1982,40672	1989,388053	1728,5464	3454,109867	2192,773333	3228,6128	1140,845067	267,5754667	6,600533333	6,600533333	0,3808	0,3808	0,3808	0,3808
REUSABLE 6	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NEW	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DEMAND	21920,11905	36614,5	68169,83333	77554,5	83725,47619	132312,4429	37126,44286	29883,44286	13621,94286	13621,94286	85,14285714	0	0	0

Under Theoretic Reuse Rates

SBS-RS

MATERIAL	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038
STOCK	29843,72778	26532,38611	31804,40278	32948,40278	27649,82897	27332,08452	22500,77341	15338,85675	10547,19008	8787,565079	2457,865079	2325,555556	1042,555556	1042,555556
INBUD	5968,745556	5306,477222	6360,880556	6589,680556	5529,965794	5466,416905	4500,154683	3067,771349	2109,438016	1757,513016	491,5730159	465,1111111	208,5111111	208,5111111
REUSABLE	23874,98222	21225,90889	25443,52222	26358,72222	22119,86317	21865,66762	18000,61873	12271,0854	8437,752063	7030,052063	1966,292063	1860,444444	834,0444444	834,0444444
NEW	106022,7733	107857,2217	131254,0583	114037,2068	87459,56348	49602,78682	60168,61348	41542,86348	27638,94682	25496,27182	13926,69848	13248,83182	5716,631818	3693,881818
DEMAND	129897,7556	129083,1306	156697,5806	140395,929	109579,4267	71468,45444	78169,23222	53813,94888	36076,69888	32526,32388	15892,99055	15109,27626	6550,676263	4527,926263

BSS-RS GR

MATERIAL	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038
STOCK	11920,25635	17027,99444	17646,14444	27392,76566	22889,68232	35142,84899	5308,987879	3203,854545	2521,354545	2505,854545	601,8545455	409,8545455	344,2545455	344,2545455
INBUD	2489,828603	3654,384222	3762,926222	5645,863798	4822,923131	7260,716465	1173,776242	658,4615758	520,0149091	516,9149091	136,1149091	97,71490909	68,85090909	68,85090909
REUSABLE	9430,427746	13373,61022	13883,21822	21746,90186	18066,75919	27882,13253	4135,211636	2545,39297	2001,339636	1988,939636	465,7396364	312,1396364	275,4036364	275,4036364
NEW	29086,23539	57178,38624	45564,26158	35880,92642	36474,52147	13770,81481	21674,67458	15389,74325	15736,29658	14516,91881	16040,11881	6814,542182	6851,278182	6851,278182
DEMAND	38516,66313	70551,99646	59447,4798	57627,82828	54541,28066	41652,94733	25809,88622	17935,13622	17737,63622	16505,85844	16505,85844	7126,681818	7126,681818	7126,681818

BSS-RS WB

MATERIAL	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038
STOCK	5635,833333	1724,333333	734,4166667	258,25	1655,25	319,5833333	20,33333333	20,33333333	20,33333333	20,33333333	20,33333333	20,33333333	0	0
INBUD	1127,166667	344,8666667	146,8833333	51,65	331,05	63,91666667	4,066666667	4,066666667	4,066666667	4,066666667	4,066666667	4,066666667	0	0
REUSABLE	4508,666667	1379,466667	587,5333333	206,6	1324,2	255,6666667	16,26666667	16,26666667	16,26666667	16,26666667	16,26666667	16,26666667	0	0
NEW	12785,11111	18434,64444	21043,99444	34586,26111	26455,82778	21975,52778	2850,9	2319,9	2063,9	2063,9	4648,9	0	0	0
DEMAND	17293,77778	19814,11111	21631,52778	34792,86111	27780,02778	22231,19444	2867,166667	2336,166667	2080,166667	2080,166667	4665,166667	0	0	0

BSS non-RS

MATERIAL	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038
STOCK 1	5752,666667	5815,008333	6818,391667	6734,831061	7765,014394	18577,36439	1902,147727	1387,597727	1387,597727	1307,472727	708,8727273	708,8727273	708,8727273	262,8727273
STOCK 2	26469,41198	25810,74293	38911,74293	36755,52323	36065,66133	27090,57799	19646,79466	19239,24466	9983,411328	9715,63355	7388,050216	4540,463636	2313,263636	2313,263636
STOCK 3	38009,98232	56669,04899	75127,13232	87094,90505	83471,20267	63116,24434	35203,97767	30961,49434	21607,911	21365,46656	16205,04989	9658,414394	6336,814394	5465,939394
STOCK 4	24269,34444	25856,30278	46789,93611	45132,17096	44723,92096	38640,07652	21381,9654	16191,43207	11604,7654	10340,6404	150,040404	150,040404	150,040404	150,040404
STOCK 5	5216,233333	5234,566667	4549,583333	9070,666667	5758,333333	8478,5	2995,916667	702,6666667	17,33333333	17,33333333	1	1	1	1
STOCK 6	1331,638889	1101,138889	1168,138889	1100,305556	1123,638889	1444,305556	686,6666667	283,9166667	122,0833333	122,0833333	0	0	0	0
INBUD 1	2070,96	2093,403	2454,621	2424,539182	2795,405182	6687,851182	684,7731818	499,5351818	499,5351818	470,6901818	255,1941818	255,1941818	255,1941818	94,63418182
INBUD 2	9918,513645	9887,579455	14755,53945	13878,62448	13647,40487	10075,51087	7613,092866	7645,203666	3946,159666	3833,055666	2846,160332	1821,029164	876,6963636	876,6963636
INBUD 3	16116,23251	24027,67677	31853,90411	36928,23974	35391,78993	27267,0156	14953,36653	13127,6736	9161,754265	9058,957821	6870,941154	4095,167703	2686,809303	2317,558303
INBUD 4	11102,0776	12933,4066	23076,7786	23599,66557	24610,34357	21252,06144	11725,5841	8937,670503	6405,830503	5708,033503	82,82230303	82,82230303	82,82230303	82,82230303
INBUD 5	2883,990133	2894,110133	2515,999333	5007,008	3178,6	4680,132	1653,746	387,872	9,568	9,568	0,552	0,552	0,552	0,552
INBUD 6	1331,638889	1101,138889	1168,138889	1100,305556	1123,638889	1444,305556	686,6666667	283,9166667	122,0833333	122,0833333	0	0	0	0
REUSABLE 1	3681,706667	3721,605333	4363,770667	4310,291879	4969,609212	11889,51321	1217,374545	888,0625455	888,0625455	836,7825455	453,6785455	453,6785455	453,6785455	168,2385455
REUSABLE 2	16550,89833	15923,16347	24156,20347	22876,89875	22418,25646	17015,06713	12033,7018	11594,041	6037,251662	5882,577884	4541,889884	2719,434473	1436,567273	1436,567273
REUSABLE 3	21893,74982	32641,37222	43273,22822	50166,66531	48079,41274	35849,22874	20250,61114	17833,82074	12446,15674	12306,50874	9334,108738	5563,246691	3650,005091	3148,381091
REUSABLE 4	13167,26684	12922,89618	23713,15751	21532,50539	20113,57739	17388,01508	9656,381301	7253,761568	5198,934901	4632,606901	67,21810101	67,21810101	67,21810101	67,21810101
REUSABLE 5	2332,2432	2340,456533	2033,584	4063,658667	2579,733333	3798,368	1342,170667	314,7946667	7,765333333	7,765333333	0,448	0,448	0,448	0,448
REUSABLE 6	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NEW	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DEMAND	21920,11905	36614,5	68169,83333	77554,5	83725,47619	132312,4429	37126,44286	29883,44286	13621,94286	13621,94286	85,14285714	0	0	0

Appendix K Storage Demand Standardised Materials

Under Realistic Reuse Rates:

- Monthly breakdown of storage demand for SBS-RS (89)
- Monthly breakdown of storage demand for BSS-RS GR (90)
- Monthly breakdown of storage demand for BSS-RS WB (91)

Under Theoretic Reuse Rates

- Monthly breakdown of storage demand for SBS-RS (92)
- Monthly breakdown of storage demand for BSS-RS GR (93)
- Monthly breakdown of storage demand for BSS-RS WB (94)

Appendix L Storage Demand Non-Standardised Materials

- Monthly breakdown of storage demand for BSS non-RS under realistic reuse rates (95)
- Monthly breakdown of storage demand for BSS non-RS under theoretic reuse rates (96)

Monthly breakdown of storage demand for BSS non-RS under realistic reuse rates

Month	To be stored 1 (m2)	To be stored 2 (m2)	To be stored 3 (m2)	To be stored 4 (m2)	To be stored 5 (m2)	To be stored 6 (m2)	Mixed material (m2)	Demand (m2)	Stored material at the start(m2)	Reuse from storage (m2)	New material needed(m2)	Non-mixable material	Material exceeding one year storage limit	Extra Inbud (m2)	Stored material at the end (m2)
2025-01	260,7875556	1172,355299	1550,807279	932,6814015	165,20056	0	3953,590789	0	0	0	0	128,2413056	0	128,2413056	3953,590789
2025-02	260,7875556	1172,355299	1550,807279	932,6814015	165,20056	0	3953,590789	1826,676587	3953,590789	1826,676587	0	128,2413056	0	128,2413056	6080,50499
2025-03	260,7875556	1172,355299	1550,807279	932,6814015	165,20056	0	3953,590789	1826,676587	6080,50499	1826,676587	0	128,2413056	0	128,2413056	8207,419191
2025-04	260,7875556	1172,355299	1550,807279	932,6814015	165,20056	0	3953,590789	1826,676587	8207,419191	1826,676587	0	128,2413056	0	128,2413056	10334,33339
2025-05	260,7875556	1172,355299	1550,807279	932,6814015	165,20056	0	3953,590789	1826,676587	10334,33339	1826,676587	0	128,2413056	0	128,2413056	12461,24759
2025-06	260,7875556	1172,355299	1550,807279	932,6814015	165,20056	0	3953,590789	1826,676587	12461,24759	1826,676587	0	128,2413056	0	128,2413056	14588,1618
2025-07	260,7875556	1172,355299	1550,807279	932,6814015	165,20056	0	3953,590789	1826,676587	14588,1618	1826,676587	0	128,2413056	0	128,2413056	16715,076
2025-08	260,7875556	1172,355299	1550,807279	932,6814015	165,20056	0	3953,590789	1826,676587	16715,076	1826,676587	0	128,2413056	0	128,2413056	18841,9002
2025-09	260,7875556	1172,355299	1550,807279	932,6814015	165,20056	0	3953,590789	1826,676587	18841,9002	1826,676587	0	128,2413056	0	128,2413056	20968,9044
2025-10	260,7875556	1172,355299	1550,807279	932,6814015	165,20056	0	3953,590789	1826,676587	20968,9044	1826,676587	0	128,2413056	0	128,2413056	23095,8186
2025-11	260,7875556	1172,355299	1550,807279	932,6814015	165,20056	0	3953,590789	1826,676587	23095,8186	1826,676587	0	128,2413056	0	128,2413056	25222,7328
2025-12	260,7875556	1172,355299	1550,807279	932,6814015	165,20056	0	3953,590789	1826,676587	25222,7328	1826,676587	0	128,2413056	0	128,2413056	27349,647
2026-01	263,6137111	1127,890746	2312,097199	915,3718126	165,7823378	0	4418,089793	1826,676587	27349,647	1826,676587	0	366,6660134	0	366,6660134	29941,06021
2026-02	263,6137111	1127,890746	2312,097199	915,3718126	165,7823378	0	4418,089793	3051,208333	29941,06021	3051,208333	0	366,6660134	0	366,6660134	31307,94167
2026-03	263,6137111	1127,890746	2312,097199	915,3718126	165,7823378	0	4418,089793	3051,208333	31307,94167	3051,208333	0	366,6660134	0	366,6660134	32674,82313
2026-04	263,6137111	1127,890746	2312,097199	915,3718126	165,7823378	0	4418,089793	3051,208333	32674,82313	3051,208333	0	366,6660134	0	366,6660134	34041,70459
2026-05	263,6137111	1127,890746	2312,097199	915,3718126	165,7823378	0	4418,089793	3051,208333	34041,70459	3051,208333	0	366,6660134	0	366,6660134	35408,58605
2026-06	263,6137111	1127,890746	2312,097199	915,3718126	165,7823378	0	4418,089793	3051,208333	35408,58605	3051,208333	0	366,6660134	0	366,6660134	36775,46751
2026-07	263,6137111	1127,890746	2312,097199	915,3718126	165,7823378	0	4418,089793	3051,208333	36775,46751	3051,208333	0	366,6660134	0	366,6660134	38142,34897
2026-08	263,6137111	1127,890746	2312,097199	915,3718126	165,7823378	0	4418,089793	3051,208333	38142,34897	3051,208333	0	366,6660134	0	366,6660134	39609,23043
2026-09	263,6137111	1127,890746	2312,097199	915,3718126	165,7823378	0	4418,089793	3051,208333	39609,23043	3051,208333	0	366,6660134	0	366,6660134	40876,11189
2026-10	263,6137111	1127,890746	2312,097199	915,3718126	165,7823378	0	4418,089793	3051,208333	40876,11189	3051,208333	0	366,6660134	0	366,6660134	42242,99335
2026-11	263,6137111	1127,890746	2312,097199	915,3718126	165,7823378	0	4418,089793	3051,208333	42242,99335	3051,208333	0	366,6660134	0	366,6660134	43609,87481
2026-12	263,6137111	1127,890746	2312,097199	915,3718126	165,7823378	0	4418,089793	3051,208333	43609,87481	3051,208333	0	366,6660134	0	366,6660134	44976,75627
2027-01	309,1004222	1711,923479	3065,186999	1679,68199	144,0455333	0	6783,21094	3051,208333	44976,75627	3051,208333	0	126,7274845	0	126,7274845	46708,75887
2027-02	309,1004222	1711,923479	3065,186999	1679,68199	144,0455333	0	6783,21094	5680,819444	46708,75887	5680,819444	0	126,7274845	0	126,7274845	48811,15037
2027-03	309,1004222	1711,923479	3065,186999	1679,68199	144,0455333	0	6783,21094	5680,819444	48811,15037	5680,819444	0	126,7274845	0	126,7274845	50913,54186
2027-04	309,1004222	1711,923479	3065,186999	1679,68199	144,0455333	0	6783,21094	5680,819444	50913,54186	5680,819444	0	126,7274845	0	126,7274845	52015,93336
2027-05	309,1004222	1711,923479	3065,186999	1679,68199	144,0455333	0	6783,21094	5680,819444	52015,93336	5680,819444	0	126,7274845	0	126,7274845	53118,32485
2027-06	309,1004222	1711,923479	3065,186999	1679,68199	144,0455333	0	6783,21094	5680,819444	53118,32485	5680,819444	0	126,7274845	0	126,7274845	54220,71635
2027-07	309,1004222	1711,923479	3065,186999	1679,68199	144,0455333	0	6783,21094	5680,819444	54220,71635	5680,819444	0	126,7274845	0	126,7274845	55323,10784
2027-08	309,1004222	1711,923479	3065,186999	1679,68199	144,0455333	0	6783,21094	5680,819444	55323,10784	5680,819444	0	126,7274845	0	126,7274845	56425,49334
2027-09	309,1004222	1711,923479	3065,186999	1679,68199	144,0455333	0	6783,21094	5680,819444	56425,49334	5680,819444	0	126,7274845	0	126,7274845	57527,89083
2027-10	309,1004222	1711,923479	3065,186999	1679,68199	144,0455333	0	6783,21094	5680,819444	57527,89083	5680,819444	0	126,7274845	0	126,7274845	58630,28233
2027-11	309,1004222	1711,923479	3065,186999	1679,68199	144,0455333	0	6783,21094	5680,819444	58630,28233	5680,819444	0	126,7274845	0	126,7274845	59732,67382
2027-12	309,1004222	1711,923479	3065,186999	1679,68199	144,0455333	0	6783,21094	5680,819444	59732,67382	5680,819444	0	126,7274845	0	126,7274845	60835,06532
2028-01	305,3123414	1621,306061	3553,472126	1525,219132	287,8424889	0	6868,735364	5680,819444	60835,06532	5680,819444	0	424,4167855	0	424,4167855	62022,98124
2028-02	305,3123414	1621,306061	3553,472126	1525,219132	287,8424889	0	6868,735364	6462,875	62022,98124	6462,875	0	424,4167855	0	424,4167855	63240,56233
2028-03	305,3123414	1621,306061	3553,472126	1525,219132	287,8424889	0	6868,735364	6462,875	64248,8416	6462,875	0	424,4167855	0	424,4167855	62834,70197
2028-04	305,3123414	1621,306061	3553,472126	1525,219132	287,8424889	0	6868,735364	6462,875	62834,70197	6462,875	0	424,4167855	0	424,4167855	63240,56233
2028-05	305,3123414	1621,306061	3553,472126	1525,219132	287,8424889	0	6868,735364	6462,875	63240,56233	6462,875	0	424,4167855	0	424,4167855	63646,42269
2028-06	305,3123414	1621,306061	3553,472126	1525,219132	287,8424889	0	6868,735364	6462,875	63646,42269	6462,875	0	424,4167855	0	424,4167855	64052,28306
2028-07	305,3123414	1621,306061	3553,472126	1525,219132	287,8424889	0	6868,735364	6462,875	64052,28306	6462,875	0	424,4167855	0	424,4167855	64458,14342
2028-08	305,3123414	1621,306061	3553,472126	1525,219132	287,8424889	0	6868,735364	6462,875	64458,14342	6462,875	0	424,4167855	0	424,4167855	64864,00379
2028-09	305,3123414	1621,306061	3553,472126	1525,219132	287,8424889	0	6868,735364	6462,875	64864,00379	6462,875	0	424,4167855	0	424,4167855	65269,86415
2028-10	305,3123414	1621,306061	3553,472126	1525,219132	287,8424889	0	6868,735364	6462,875	65269,86415	6462,875	0	424,4167855	0	424,4167855	65675,72451
2028-11	305,3123414	1621,306061	3553,472126	1525,219132	287,8424889	0	6868,735364	6462,875	65675,72451	6462,875	0	424,4167855	0	424,4167855	66081,58488
2028-12	305,3123414	1621,306061	3553,472126	1525,219132	287,8424889	0	6868,735364	6462,875	66081,58488	6462,875	0	424,4167855	0	424,4167855	66487,44524
2029-01	352,0139859	1588,818899	3405,625069	1424,711732	182,7311111	0	6392,523485	6462,875	66487,44524	6462,875	0	561,3773125	0	561,3773125	66417,09373
2029-02	352,0139859	1588,818899	3405,625069	1424,711732	182,7311111	0	6392,523485	6977,123016	66417,09373	6977,123016	0	561,3773125	0	561,3773125	66832,4942
2029-03	352,0139859	1588,818899	3405,625069	1424,711732	182,7311111	0	6392,523485	6977,123016	66832,4942	6977,123016	0	561,3773125	0	561,3773125	65247,89466
2029-04	352,0139859	1588,818899	3405,625069	1424,711732	182,7311111	0	6392,523485	6977,123016	65247,89466	6977,123016	0	561,3773125	0	561,3773125	64663,29513
2029-05	352,0139859	1588,818899	3405,625069	1424,711732	182,7311111	0	6392,523485	6977,123016	64663,29513	6977,123016	0	561,3773125	0	561,3773125	64078,6956
2029-06	352,0139859	1588,818899	3405,625069	1424,711732	182,7311111	0	6392,523485	6977,123016	64078,6956	6977,123016	0	561,3773125	0	561,3773125	63494,09607
2029-07	352,0139859	1588,818899	3405,625069	1424,711732	182,7311111	0	6392								

Monthly breakdown of storage demand for BSS non-RS under theoretic reuse rates

Month	To be stored 1 (m2)	To be stored 2 (m2)	To be stored 3 (m2)	To be stored 4 (m2)	To be stored 5 (m2)	To be stored 6 (m2)	Mixed material (m2)	Demand (m2)	Stored material at the start(m2)	Reuse from storage (m2)	New material needed(m2)	Non-mixable material	Material exceeding one year storage limit	Extra Inbnd (m2)	Stored material at the end (m2)
2025-01	306,8088889	1379,241528	1824,479152	1097,272237	194,3536	0	4651,283281	0	0	0	0	0	150,8721243	0	4651,283281
2025-02	306,8088889	1379,241528	1824,479152	1097,272237	194,3536	0	4651,283281	1826,676587	4651,283281	1826,676587	0	0	150,8721243	0	7475,889974
2025-03	306,8088889	1379,241528	1824,479152	1097,272237	194,3536	0	4651,283281	1826,676587	7475,889974	1826,676587	0	0	150,8721243	0	10300,49667
2025-04	306,8088889	1379,241528	1824,479152	1097,272237	194,3536	0	4651,283281	1826,676587	10300,49667	1826,676587	0	0	150,8721243	0	13125,10336
2025-05	306,8088889	1379,241528	1824,479152	1097,272237	194,3536	0	4651,283281	1826,676587	13125,10336	1826,676587	0	0	150,8721243	0	15949,71005
2025-06	306,8088889	1379,241528	1824,479152	1097,272237	194,3536	0	4651,283281	1826,676587	15949,71005	1826,676587	0	0	150,8721243	0	18774,31675
2025-07	306,8088889	1379,241528	1824,479152	1097,272237	194,3536	0	4651,283281	1826,676587	18774,31675	1826,676587	0	0	150,8721243	0	21589,92344
2025-08	306,8088889	1379,241528	1824,479152	1097,272237	194,3536	0	4651,283281	1826,676587	21589,92344	1826,676587	0	0	150,8721243	0	24423,53014
2025-09	306,8088889	1379,241528	1824,479152	1097,272237	194,3536	0	4651,283281	1826,676587	24423,53014	1826,676587	0	0	150,8721243	0	27248,13683
2025-10	306,8088889	1379,241528	1824,479152	1097,272237	194,3536	0	4651,283281	1826,676587	27248,13683	1826,676587	0	0	150,8721243	0	30072,74352
2025-11	306,8088889	1379,241528	1824,479152	1097,272237	194,3536	0	4651,283281	1826,676587	30072,74352	1826,676587	0	0	150,8721243	0	32897,35022
2025-12	306,8088889	1379,241528	1824,479152	1097,272237	194,3536	0	4651,283281	1826,676587	32897,35022	1826,676587	0	0	150,8721243	0	35721,95691
2026-01	310,1337778	1326,93029	2720,114352	1076,908015	195,0380444	0	5197,752698	1826,676587	35721,95691	1826,676587	0	0	431,3717805	0	39093,03302
2026-02	310,1337778	1326,93029	2720,114352	1076,908015	195,0380444	0	5197,752698	3051,208333	39093,03302	3051,208333	0	0	431,3717805	0	41239,57738
2026-03	310,1337778	1326,93029	2720,114352	1076,908015	195,0380444	0	5197,752698	3051,208333	41239,57738	3051,208333	0	0	431,3717805	0	43386,12175
2026-04	310,1337778	1326,93029	2720,114352	1076,908015	195,0380444	0	5197,752698	3051,208333	43386,12175	3051,208333	0	0	431,3717805	0	45532,66611
2026-05	310,1337778	1326,93029	2720,114352	1076,908015	195,0380444	0	5197,752698	3051,208333	45532,66611	3051,208333	0	0	431,3717805	0	47679,21048
2026-06	310,1337778	1326,93029	2720,114352	1076,908015	195,0380444	0	5197,752698	3051,208333	47679,21048	3051,208333	0	0	431,3717805	0	49825,75484
2026-07	310,1337778	1326,93029	2720,114352	1076,908015	195,0380444	0	5197,752698	3051,208333	49825,75484	3051,208333	0	0	431,3717805	0	51972,29921
2026-08	310,1337778	1326,93029	2720,114352	1076,908015	195,0380444	0	5197,752698	3051,208333	51972,29921	3051,208333	0	0	431,3717805	0	54118,84357
2026-09	310,1337778	1326,93029	2720,114352	1076,908015	195,0380444	0	5197,752698	3051,208333	54118,84357	3051,208333	0	0	431,3717805	0	56265,38793
2026-10	310,1337778	1326,93029	2720,114352	1076,908015	195,0380444	0	5197,752698	3051,208333	56265,38793	3051,208333	0	0	431,3717805	0	58411,9323
2026-11	310,1337778	1326,93029	2720,114352	1076,908015	195,0380444	0	5197,752698	3051,208333	58411,9323	3051,208333	0	0	431,3717805	0	60584,47666
2026-12	310,1337778	1326,93029	2720,114352	1076,908015	195,0380444	0	5197,752698	3051,208333	60584,47666	3051,208333	0	0	431,3717805	331,9886554	62373,03237
2027-01	363,6475556	2013,016956	3606,102352	1976,096459	169,4653333	0	7978,226831	3051,208333	62373,03237	3051,208333	0	0	150,1018249	2146,544364	65153,50651
2027-02	363,6475556	2013,016956	3606,102352	1976,096459	169,4653333	0	7978,226831	5680,819444	65153,50651	5680,819444	0	0	150,1018249	0	67450,91389
2027-03	363,6475556	2013,016956	3606,102352	1976,096459	169,4653333	0	7978,226831	5680,819444	67450,91389	5680,819444	0	0	150,1018249	0	69748,32128
2027-04	363,6475556	2013,016956	3606,102352	1976,096459	169,4653333	0	7978,226831	5680,819444	69748,32128	5680,819444	0	0	150,1018249	0	72045,72866
2027-05	363,6475556	2013,016956	3606,102352	1976,096459	169,4653333	0	7978,226831	5680,819444	72045,72866	5680,819444	0	0	150,1018249	0	74343,13605
2027-06	363,6475556	2013,016956	3606,102352	1976,096459	169,4653333	0	7978,226831	5680,819444	74343,13605	5680,819444	0	0	150,1018249	0	76640,54344
2027-07	363,6475556	2013,016956	3606,102352	1976,096459	169,4653333	0	7978,226831	5680,819444	76640,54344	5680,819444	0	0	150,1018249	0	78937,95082
2027-08	363,6475556	2013,016956	3606,102352	1976,096459	169,4653333	0	7978,226831	5680,819444	78937,95082	5680,819444	0	0	150,1018249	0	81235,35821
2027-09	363,6475556	2013,016956	3606,102352	1976,096459	169,4653333	0	7978,226831	5680,819444	81235,35821	5680,819444	0	0	150,1018249	0	83532,7656
2027-10	363,6475556	2013,016956	3606,102352	1976,096459	169,4653333	0	7978,226831	5680,819444	83532,7656	5680,819444	0	0	150,1018249	0	85830,17298
2027-11	363,6475556	2013,016956	3606,102352	1976,096459	169,4653333	0	7978,226831	5680,819444	85830,17298	5680,819444	0	0	150,1018249	0	88127,58037
2027-12	363,6475556	2013,016956	3606,102352	1976,096459	169,4653333	0	7978,226831	5680,819444	88127,58037	5680,819444	0	0	150,1018249	0	90424,98776
2028-01	359,1909899	1906,408229	4180,555442	1794,375449	338,6382222	0	8078,843801	5680,819444	90424,98776	5680,819444	0	0	500,324532	0	92823,01211
2028-02	359,1909899	1906,408229	4180,555442	1794,375449	338,6382222	0	8078,843801	6462,875	92823,01211	6462,875	0	0	500,324532	0	94439,98091
2028-03	359,1909899	1906,408229	4180,555442	1794,375449	338,6382222	0	8078,843801	6462,875	94439,98091	6462,875	0	14,37683367	1515,351831	2015,676363	96040,32458
2028-04	359,1909899	1906,408229	4180,555442	1794,375449	338,6382222	0	8078,843801	6462,875	96040,57288	6462,875	0	0	500,324532	0	96141,18985
2028-05	359,1909899	1906,408229	4180,555442	1794,375449	338,6382222	0	8078,843801	6462,875	96141,18985	6462,875	0	0	500,324532	0	96241,80682
2028-06	359,1909899	1906,408229	4180,555442	1794,375449	338,6382222	0	8078,843801	6462,875	96241,80682	6462,875	0	0	500,324532	0	96342,42379
2028-07	359,1909899	1906,408229	4180,555442	1794,375449	338,6382222	0	8078,843801	6462,875	96342,42379	6462,875	0	0	500,324532	0	96443,04076
2028-08	359,1909899	1906,408229	4180,555442	1794,375449	338,6382222	0	8078,843801	6462,875	96443,04076	6462,875	0	0	500,324532	0	96543,65773
2028-09	359,1909899	1906,408229	4180,555442	1794,375449	338,6382222	0	8078,843801	6462,875	96543,65773	6462,875	0	0	500,324532	0	96644,2747
2028-10	359,1909899	1906,408229	4180,555442	1794,375449	338,6382222	0	8078,843801	6462,875	96644,2747	6462,875	0	0	500,324532	0	96744,89167
2028-11	359,1909899	1906,408229	4180,555442	1794,375449	338,6382222	0	8078,843801	6462,875	96744,89167	6462,875	0	0	500,324532	0	96845,50864
2028-12	359,1909899	1906,408229	4180,555442	1794,375449	338,6382222	0	8078,843801	6462,875	96845,50864	6462,875	0	0	500,324532	0	96946,12561
2029-01	414,134101	1868,188038	4006,617728	1676,131449	214,9777778	0	7518,594531	6462,875	96946,12561	6462,875	0	0	661,4545637	1615,968801	96385,87634
2029-02	414,134101	1868,188038	4006,617728	1676,131449	214,9777778	0	7518,594531	6977,123016	96385,87634	6977,123016	0	0	1101,720785	1763,175349	95625,62707
2029-03	414,134101	1868,188038	4006,617728	1676,131449	214,9777778	0	7518,594531	6977,123016	95625,62707	6977,123016	0	0	1101,720785	1763,175349	96265,3778
2029-04	414,134101	1868,188038	4006,617728	1676,131449	214,9777778	0	7518,594531	6977,123016	96265,3778	6977,123016	0	0	1101,720785	1763,175349	94705,12853
2029-05	414,134101	1868,188038	4006,617728	1676,131449	214,9777778	0	7518,594531	6977,123016	94705,12853	6977,123016	0	0	1101,720785	1763,175349	94144,87926
2029-06	414,134101	1868,188038	4006,617728	1676,131449	214,9777778	0	7518,594531	6977,123016	94144,87926	6977,123016	0	0	1101,720785	1763,175349	93584,62999
2029-07	414,134101	1868,188038	4006,617728	1676,131449	214,9777778	0	7518,594531	6977,123016	93584,62999	6977,123016	0	0	1101,720785	1763,175349	93024,38072
2029-08	414,134101	1868,188038	4006,617728	1676,131449	214,9777778	0	7518,594531	6977,123016	93024,38072	6977,123016	0	0	1101,720785	1763,175349	92464,33145
2029-09	414,134101	1868,188038	4006,617728	1676,131449	214,9777778										

Appendix M Storage Demand Standardised Materials under Adjusted Project Planning

Under Realistic Reuse Rates

MONTH	CURRENT STORAGE DEMAND (TOTAL)	ACTUAL FLATTENED STORAGE DEMAND (TOTAL)	MAXIMUM FLATTENED STORAGE DEMAND (TOTAL)
2025-01	2437,062868	2651,596201	2731,863612
2025-02	2437,062868	2651,596201	2731,863612
2025-03	2437,062868	2651,596201	2731,863612
2025-04	2437,062868	2651,596201	2731,863612
2025-05	2437,062868	2651,596201	2731,863612
2025-06	2437,062868	2651,596201	2731,863612
2025-07	2437,062868	2651,596201	2731,863612
2025-08	2437,062868	2651,596201	2731,863612
2025-09	2437,062868	2651,596201	2731,863612
2025-10	2437,062868	2651,596201	2731,863612
2025-11	2437,062868	2651,596201	2731,863612
2025-12	2437,062868	2651,596201	2731,863612
2026-01	2249,169898	2707,226564	2731,863612
2026-02	2249,169898	2707,226564	2731,863612
2026-03	2249,169898	2707,226564	2731,863612
2026-04	2249,169898	2707,226564	2731,863612
2026-05	2249,169898	2707,226564	2731,863612
2026-06	2249,169898	2707,226564	2731,863612
2026-07	2249,169898	2707,226564	2731,863612
2026-08	2249,169898	2707,226564	2731,863612
2026-09	2249,169898	2707,226564	2731,863612
2026-10	2249,169898	2707,226564	2731,863612
2026-11	2249,169898	2707,226564	2731,863612
2026-12	2249,169898	2707,226564	2731,863612
2027-01	2502,438631	2648,290298	2731,863612
2027-02	2502,438631	2648,290298	2731,863612
2027-03	2502,438631	2648,290298	2731,863612
2027-04	2502,438631	2648,290298	2731,863612
2027-05	2502,438631	2648,290298	2731,863612
2027-06	2502,438631	2648,290298	2731,863612
2027-07	2502,438631	2648,290298	2731,863612
2027-08	2502,438631	2648,290298	2731,863612
2027-09	2502,438631	2648,290298	2731,863612
2027-10	2502,438631	2648,290298	2731,863612
2027-11	2502,438631	2648,290298	2731,863612
2027-12	2502,438631	2648,290298	2731,863612
2028-01	3134,445184	2963,696851	2731,863612
2028-02	3134,445184	2963,696851	2731,863612
2028-03	3134,445184	2963,696851	2731,863612
2028-04	3134,445184	2963,696851	2731,863612
2028-05	3134,445184	2963,696851	2731,863612
2028-06	3134,445184	2963,696851	2731,863612
2028-07	3134,445184	2963,696851	2731,863612
2028-08	3134,445184	2963,696851	2731,863612
2028-09	3134,445184	2963,696851	2731,863612
2028-10	3134,445184	2963,696851	2731,863612
2028-11	3134,445184	2963,696851	2731,863612
2028-12	3134,445184	2963,696851	2731,863612
2029-01	2719,207043	2573,355376	2731,863612
2029-02	2719,207043	2573,355376	2731,863612
2029-03	2719,207043	2573,355376	2731,863612
2029-04	2719,207043	2573,355376	2731,863612
2029-05	2719,207043	2573,355376	2731,863612
2029-06	2719,207043	2573,355376	2731,863612
2029-07	2719,207043	2573,355376	2731,863612
2029-08	2719,207043	2573,355376	2731,863612
2029-09	2719,207043	2573,355376	2731,863612
2029-10	2719,207043	2573,355376	2731,863612
2029-11	2719,207043	2573,355376	2731,863612
2029-12	2719,207043	2573,355376	2731,863612
2030-01	3348,858047	2847,016381	2731,863612
2030-02	3348,858047	2847,016381	2731,863612
2030-03	3348,858047	2847,016381	2731,863612
2030-04	3348,858047	2847,016381	2731,863612
2030-05	3348,858047	2847,016381	2731,863612
2030-06	3348,858047	2847,016381	2731,863612
2030-07	3348,858047	2847,016381	2731,863612
2030-08	3348,858047	2847,016381	2731,863612
2030-09	3348,858047	2847,016381	2731,863612
2030-10	3348,858047	2847,016381	2731,863612
2030-11	3348,858047	2847,016381	2731,863612
2030-12	3348,858047	2847,016381	2731,863612

Appendices

Under Realistic Reuse Rates

MONTH	CURRENT STORAGE DEMAND (TOTAL)	ACTUAL FLATTENED STORAGE DEMAND (TOTAL)	MAXIMUM FLATTENED STORAGE DEMAND (TOTAL)
2025-01	3151,173053	3425,99972	3521,303465
2025-02	3151,173053	3425,99972	3521,303465
2025-03	3151,173053	3425,99972	3521,303465
2025-04	3151,173053	3425,99972	3521,303465
2025-05	3151,173053	3425,99972	3521,303465
2025-06	3151,173053	3425,99972	3521,303465
2025-07	3151,173053	3425,99972	3521,303465
2025-08	3151,173053	3425,99972	3521,303465
2025-09	3151,173053	3425,99972	3521,303465
2025-10	3151,173053	3425,99972	3521,303465
2025-11	3151,173053	3425,99972	3521,303465
2025-12	3151,173053	3425,99972	3521,303465
2026-01	2998,248815	3563,215481	3521,303465
2026-02	2998,248815	3563,215481	3521,303465
2026-03	2998,248815	3563,215481	3521,303465
2026-04	2998,248815	3563,215481	3521,303465
2026-05	2998,248815	3563,215481	3521,303465
2026-06	2998,248815	3563,215481	3521,303465
2026-07	2998,248815	3563,215481	3521,303465
2026-08	2998,248815	3563,215481	3521,303465
2026-09	2998,248815	3563,215481	3521,303465
2026-10	2998,248815	3563,215481	3521,303465
2026-11	2998,248815	3563,215481	3521,303465
2026-12	2998,248815	3563,215481	3521,303465
2027-01	3326,189481	3523,856148	3521,303465
2027-02	3326,189481	3523,856148	3521,303465
2027-03	3326,189481	3523,856148	3521,303465
2027-04	3326,189481	3523,856148	3521,303465
2027-05	3326,189481	3523,856148	3521,303465
2027-06	3326,189481	3523,856148	3521,303465
2027-07	3326,189481	3523,856148	3521,303465
2027-08	3326,189481	3523,856148	3521,303465
2027-09	3326,189481	3523,856148	3521,303465
2027-10	3326,189481	3523,856148	3521,303465
2027-11	3326,189481	3523,856148	3521,303465
2027-12	3326,189481	3523,856148	3521,303465
2028-01	4026,018673	3795,08534	3521,303465
2028-02	4026,018673	3795,08534	3521,303465
2028-03	4026,018673	3795,08534	3521,303465
2028-04	4026,018673	3795,08534	3521,303465
2028-05	4026,018673	3795,08534	3521,303465
2028-06	4026,018673	3795,08534	3521,303465
2028-07	4026,018673	3795,08534	3521,303465
2028-08	4026,018673	3795,08534	3521,303465
2028-09	4026,018673	3795,08534	3521,303465
2028-10	4026,018673	3795,08534	3521,303465
2028-11	4026,018673	3795,08534	3521,303465
2028-12	4026,018673	3795,08534	3521,303465
2029-01	3459,235197	3261,568531	3521,303465
2029-02	3459,235197	3261,568531	3521,303465
2029-03	3459,235197	3261,568531	3521,303465
2029-04	3459,235197	3261,568531	3521,303465
2029-05	3459,235197	3261,568531	3521,303465
2029-06	3459,235197	3261,568531	3521,303465
2029-07	3459,235197	3261,568531	3521,303465
2029-08	3459,235197	3261,568531	3521,303465
2029-09	3459,235197	3261,568531	3521,303465
2029-10	3459,235197	3261,568531	3521,303465
2029-11	3459,235197	3261,568531	3521,303465
2029-12	3459,235197	3261,568531	3521,303465
2030-01	4166,955568	3558,095568	3521,303465
2030-02	4166,955568	3558,095568	3521,303465
2030-03	4166,955568	3558,095568	3521,303465
2030-04	4166,955568	3558,095568	3521,303465
2030-05	4166,955568	3558,095568	3521,303465
2030-06	4166,955568	3558,095568	3521,303465
2030-07	4166,955568	3558,095568	3521,303465
2030-08	4166,955568	3558,095568	3521,303465
2030-09	4166,955568	3558,095568	3521,303465
2030-10	4166,955568	3558,095568	3521,303465
2030-11	4166,955568	3558,095568	3521,303465
2030-12	4166,955568	3558,095568	3521,303465

Appendix N Storage Demand Non-Standardised Materials under Adjusted Project Planning

Under Realistic Reuse Rates

MONTH	CURRENT STORAGE DEMAND (TOTAL)	ACTUAL FLATTENED STORAGE DEMAND (TOTAL)	MAXIMUM FLATTENED STORAGE DEMAND (TOTAL)
2025-01	3953,590789	3962,207749	43980,14066
2025-02	6080,50499	6022,672243	43980,14066
2025-03	8207,419191	8083,136738	43980,14066
2025-04	10334,33339	10143,60123	43980,14066
2025-05	12461,24759	12204,06573	43980,14066
2025-06	14588,1618	14264,53022	43980,14066
2025-07	16715,076	16324,99472	43980,14066
2025-08	18841,9902	18385,45921	43980,14066
2025-09	20968,9044	20445,92371	43980,14066
2025-10	23095,8186	22506,3882	43980,14066
2025-11	25222,7328	24566,8527	43980,14066
2025-12	27349,647	26627,31719	43980,14066
2026-01	29941,06021	29147,25413	43980,14066
2026-02	31307,94167	30517,72599	43980,14066
2026-03	32674,82313	31888,19785	43980,14066
2026-04	34041,70459	33258,66971	43980,14066
2026-05	35408,58605	34629,14157	43980,14066
2026-06	36775,46751	35999,61343	43980,14066
2026-07	38142,34897	37370,08529	43980,14066
2026-08	39509,23043	38740,55715	43980,14066
2026-09	40876,11189	40111,02901	43980,14066
2026-10	42242,99335	41481,50087	43980,14066
2026-11	43609,87481	42851,97273	43980,14066
2026-12	44976,75627	44222,44459	43980,14066
2027-01	48708,75887	47958,03759	43980,14066
2027-02	49811,15037	49064,01949	43980,14066
2027-03	50913,54186	50170,00138	43980,14066
2027-04	52015,93336	51275,98328	43980,14066
2027-05	53118,32485	52381,96517	43980,14066
2027-06	54220,71635	53487,94707	43980,14066
2027-07	55323,10784	54593,92896	43980,14066
2027-08	56425,49934	55699,91086	43980,14066
2027-09	57527,89083	56805,89275	43980,14066
2027-10	58630,28233	57911,87465	43980,14066
2027-11	59732,67382	59017,85654	43980,14066
2027-12	60835,06532	60123,83844	43980,14066
2028-01	62022,98124	61306,9188	43980,14066
2028-02	62428,8416	61707,94361	43980,14066
2028-03	62834,70197	62108,96842	43980,14066
2028-04	63240,56233	62509,99323	43980,14066
2028-05	63646,42269	62911,01804	43980,14066
2028-06	64052,28306	63312,04285	43980,14066
2028-07	64458,14342	63713,06765	43980,14066
2028-08	64864,00379	64114,09246	43980,14066
2028-09	65269,86415	64515,11727	43980,14066
2028-10	65675,72451	64916,14208	43980,14066
2028-11	66081,58488	65317,16689	43980,14066
2028-12	66487,44524	65718,1917	43980,14066
2029-01	66417,09373	65644,24978	43980,14066
2029-02	65832,4942	65056,05985	43980,14066
2029-03	65247,89466	64467,86992	43980,14066
2029-04	64663,29513	63879,67999	43980,14066
2029-05	64078,6956	63291,49005	43980,14066
2029-06	63494,09607	62703,30012	43980,14066
2029-07	62909,49654	62115,11019	43980,14066
2029-08	62324,89701	61526,92026	43980,14066
2029-09	61740,29748	60938,73033	43980,14066
2029-10	61155,69794	60350,5404	43980,14066
2029-11	60571,09841	59762,35047	43980,14066
2029-12	59986,49888	59174,16054	43980,14066
2030-01	58422,96611	57607,03737	43980,14066
2030-02	52810,51945	52066,06697	43980,14066
2030-03	47198,07279	46525,09658	43980,14066
2030-04	41585,62614	40984,12619	43980,14066
2030-05	35973,17948	35443,1558	43980,14066
2030-06	30360,73282	29902,18541	43980,14066
2030-07	24748,28616	24361,21501	43980,14066
2030-08	19135,8395	18820,24462	43980,14066
2030-09	13523,39284	13279,27423	43980,14066
2030-10	7910,946183	7738,303837	43980,14066
2030-11	5413,590246	5409,999846	43980,14066
2030-12	5413,590246	5409,999846	43980,14066

Appendices

Under Realistic Reuse Rates

MONTH	CURRENT STORAGE DEMAND (TOTAL)	ACTUAL FLATTENED STORAGE DEMAND (TOTAL)	MAXIMUM FLATTENED STORAGE DEMAND (TOTAL)
2025-01	4651,283281	4661,420881	66935,71093
2025-02	7475,889974	7421,098508	66935,71093
2025-03	10300,49667	10180,77613	66935,71093
2025-04	13125,10336	12940,45376	66935,71093
2025-05	15949,71005	15700,13139	66935,71093
2025-06	18774,31675	18459,80902	66935,71093
2025-07	21598,92344	21219,48664	66935,71093
2025-08	24423,53014	23979,16427	66935,71093
2025-09	27248,13683	26738,8419	66935,71093
2025-10	30072,74352	29498,51952	66935,71093
2025-11	32897,35022	32258,19715	66935,71093
2025-12	35721,95691	35017,87478	66935,71093
2026-01	39093,03302	38318,10822	66935,71093
2026-02	41239,57738	40468,87658	66935,71093
2026-03	43386,12175	42619,64495	66935,71093
2026-04	45532,66611	44770,41331	66935,71093
2026-05	47679,21048	46921,18168	66935,71093
2026-06	49825,75484	49071,95004	66935,71093
2026-07	51972,29921	51222,71841	66935,71093
2026-08	54118,84357	53373,48677	66935,71093
2026-09	56265,38793	55524,25513	66935,71093
2026-10	58411,9323	57675,0235	66935,71093
2026-11	60558,47666	59825,79186	66935,71093
2026-12	62373,03237	61976,56023	66935,71093
2027-01	65153,50651	65204,19451	66935,71093
2027-02	67450,91389	67505,82589	66935,71093
2027-03	69748,32128	69807,45728	66935,71093
2027-04	72045,72866	72109,08866	66935,71093
2027-05	74343,13605	74410,72005	66935,71093
2027-06	76640,54344	76712,35144	66935,71093
2027-07	78937,95082	79013,98282	66935,71093
2027-08	81235,35821	81315,61421	66935,71093
2027-09	83532,7656	83617,2456	66935,71093
2027-10	85830,17298	85918,87698	66935,71093
2027-11	88127,58037	88220,50837	66935,71093
2027-12	90424,98776	90522,13976	66935,71093
2028-01	92823,01211	92914,47522	66935,71093
2028-02	94438,98091	94524,75514	66935,71093
2028-03	96040,57288	96061,52221	66935,71093
2028-04	96141,18985	96152,22629	66935,71093
2028-05	96241,80682	96242,93038	66935,71093
2028-06	96342,42379	96333,63446	66935,71093
2028-07	96443,04076	96424,33854	66935,71093
2028-08	96543,65773	96515,04262	66935,71093
2028-09	96644,2747	96605,7467	66935,71093
2028-10	96744,89167	96696,45078	66935,71093
2028-11	96845,50864	96787,15486	66935,71093
2028-12	96946,12561	96877,85894	66935,71093
2029-01	96385,87634	96319,07456	66935,71093
2029-02	95825,62707	95760,29018	66935,71093
2029-03	95265,3778	95201,5058	66935,71093
2029-04	94705,12853	94642,72142	66935,71093
2029-05	94144,87926	94083,93704	66935,71093
2029-06	93584,62999	93525,15266	66935,71093
2029-07	93024,38072	92966,36827	66935,71093
2029-08	92464,13145	92407,58389	66935,71093
2029-09	91903,88218	91848,79951	66935,71093
2029-10	91343,63291	91290,01513	66935,71093
2029-11	90783,38364	90731,23075	66935,71093
2029-12	90223,13437	90172,44637	66935,71093
2030-01	89071,44821	89020,76021	66935,71093
2030-02	84412,31967	84432,47434	66935,71093
2030-03	79753,19113	79844,18847	66935,71093
2030-04	75094,0626	75255,9026	66935,71093
2030-05	70434,93406	70667,61673	66935,71093
2030-06	65775,80552	66079,33086	66935,71093
2030-07	61116,67699	61491,04499	66935,71093
2030-08	56457,54845	56902,75912	66935,71093
2030-09	51798,41991	52314,47325	66935,71093
2030-10	47139,29137	47726,18737	66935,71093
2030-11	42480,16284	43137,9015	66935,71093
2030-12	37821,0343	38549,61563	66935,71093

Appendix O Material Flows under Adjusted Project Design

Under Realistic Reuse Rates

MATERIAL	STOCK	INBUD	REUSABLE	NEW	DEMAND
BSS-RS GR	147259,9619	48367,51074	98892,45116	339320,1655	177696
BSS non-RS	1212434,719	639471,9148	572962,8043		0 775152,4024
BSS non-RS 1	59837,58333	27285,938	32551,64533		0 0
BSS non-RS 2	266243,7857	126273,4095	139970,3762		0 0
BSS non-RS 3	550293,5833	281322,5617	268971,0216		0 0
BSS non-RS 4	285530,7167	170059,9375	115470,7791		0 0
BSS non-RS 5	42045,13333	26046,15136	15998,98197		0 0
BSS non-RS 6	8483,916667	8483,916667	0	0	0
TOTAL	1359694,681	687839,4255	671855,2554	339320,1655	952848,4024

Under Theoretic Reuse Rates

MATERIAL	STOCK	INBUD	REUSABLE	NEW	DEMAND
BSS-RS GR	147259,9619	30877,34171	116382,6202	321829,9965	177696
BSS non-RS	1212434,719	538409,3437	674025,3754		0 775152,4024
BSS non-RS 1	59837,58333	21541,53	38296,05333		0 0
BSS non-RS 2	266243,7857	101621,2669	164622,5189		0 0
BSS non-RS 3	550293,5833	233857,0873	316436,496		0 0
BSS non-RS 4	285530,7167	149682,7412	135847,9755		0 0
BSS non-RS 5	42045,13333	23222,8016	18822,33173		0 0
BSS non-RS 6	8483,916667	8483,916667	0	0	0
TOTAL	1359694,681	569286,6854	790407,9956	321829,9965	952848,4024

Appendix P Storage Demand Standardised Materials under Adjusted Project Design

- Monthly breakdown of storage demand for BSS RS under realistic reuse rates (104)
- Monthly breakdown of storage demand for BSS RS under theoretic reuse rates (105)

Appendix Q Storage Demand Non-Standardised Materials under Adjusted Project Design

- Monthly breakdown of storage demand for BSS non-RS under realistic reuse rates (95)
- Monthly breakdown of storage demand for BSS non-RS under theoretic reuse rates (96)

Monthly breakdown of storage demand for BSS non-RS under theoretic reuse rates

Month	To be stored 1 (m2)	To be stored 2 (m2)	To be stored 3 (m2)	To be stored 4 (m2)	To be stored 5 (m2)	To be stored 6 (m2)	Mixed material (m2)	Demand (m2)	Stored material at the start(m2)	Reuse from storage (m2)	New material needed(m2)	Non-mixable material	Material exceeding one year storage limit	Extra Inbud (m2)	Stored material at the end (m2)
2025-01	306,8088889	1379,241528	1824,479152	1097,272237	194,3536	0	4651,283281	0	0	0	0	0	150,8721243	0	4651,283281
2025-02	306,8088889	1379,241528	1824,479152	1097,272237	194,3536	0	4651,283281	3942,134626	4651,283281	3942,134626	0	0	150,8721243	0	5360,431936
2025-03	306,8088889	1379,241528	1824,479152	1097,272237	194,3536	0	4651,283281	3942,134626	5360,431936	3942,134626	0	0	150,8721243	0	6069,58059
2025-04	306,8088889	1379,241528	1824,479152	1097,272237	194,3536	0	4651,283281	3942,134626	6069,58059	3942,134626	0	0	150,8721243	0	6778,729245
2025-05	306,8088889	1379,241528	1824,479152	1097,272237	194,3536	0	4651,283281	3942,134626	6778,729245	3942,134626	0	0	150,8721243	0	7487,8779
2025-06	306,8088889	1379,241528	1824,479152	1097,272237	194,3536	0	4651,283281	3942,134626	7487,8779	3942,134626	0	0	150,8721243	0	8197,026555
2025-07	306,8088889	1379,241528	1824,479152	1097,272237	194,3536	0	4651,283281	3942,134626	8197,026555	3942,134626	0	0	150,8721243	0	8906,17521
2025-08	306,8088889	1379,241528	1824,479152	1097,272237	194,3536	0	4651,283281	3942,134626	8906,17521	3942,134626	0	0	150,8721243	0	9615,323864
2025-09	306,8088889	1379,241528	1824,479152	1097,272237	194,3536	0	4651,283281	3942,134626	9615,323864	3942,134626	0	0	150,8721243	0	10324,47252
2025-10	306,8088889	1379,241528	1824,479152	1097,272237	194,3536	0	4651,283281	3942,134626	10324,47252	3942,134626	0	0	150,8721243	0	11033,62117
2025-11	306,8088889	1379,241528	1824,479152	1097,272237	194,3536	0	4651,283281	3942,134626	11033,62117	3942,134626	0	0	150,8721243	0	11742,76983
2025-12	306,8088889	1379,241528	1824,479152	1097,272237	194,3536	0	4651,283281	3942,134626	11742,76983	3942,134626	0	0	150,8721243	0	12451,91848
2026-01	310,1337778	1326,93029	2720,114352	1076,908015	195,0380444	0	5197,752698	3942,134626	12451,91848	3942,134626	0	0	431,3717805	0	13707,53656
2026-02	310,1337778	1326,93029	2720,114352	1076,908015	195,0380444	0	5197,752698	3942,134626	13707,53656	5162,958039	0	0	431,3717805	0	13742,33121
2026-03	310,1337778	1326,93029	2720,114352	1076,908015	195,0380444	0	5197,752698	3942,134626	13742,33121	5162,958039	0	0	431,3717805	0	13777,12587
2026-04	310,1337778	1326,93029	2720,114352	1076,908015	195,0380444	0	5197,752698	3942,134626	13777,12587	5162,958039	0	0	431,3717805	0	13811,92053
2026-05	310,1337778	1326,93029	2720,114352	1076,908015	195,0380444	0	5197,752698	3942,134626	13811,92053	5162,958039	0	0	431,3717805	0	13846,71519
2026-06	310,1337778	1326,93029	2720,114352	1076,908015	195,0380444	0	5197,752698	3942,134626	13846,71519	5162,958039	0	0	431,3717805	0	13881,50985
2026-07	310,1337778	1326,93029	2720,114352	1076,908015	195,0380444	0	5197,752698	3942,134626	13881,50985	5162,958039	0	0	431,3717805	0	13916,30451
2026-08	310,1337778	1326,93029	2720,114352	1076,908015	195,0380444	0	5197,752698	3942,134626	13916,30451	5162,958039	0	0	431,3717805	0	13951,09917
2026-09	310,1337778	1326,93029	2720,114352	1076,908015	195,0380444	0	5197,752698	3942,134626	13951,09917	5162,958039	0	0	431,3717805	0	13986,89383
2026-10	310,1337778	1326,93029	2720,114352	1076,908015	195,0380444	0	5197,752698	3942,134626	13986,89383	5162,958039	0	0	431,3717805	0	14020,68849
2026-11	310,1337778	1326,93029	2720,114352	1076,908015	195,0380444	0	5197,752698	3942,134626	14020,68849	5162,958039	0	0	431,3717805	0	14056,48314
2026-12	310,1337778	1326,93029	2720,114352	1076,908015	195,0380444	0	5197,752698	3942,134626	14056,48314	5162,958039	0	0	431,3717805	0	14090,2778
2027-01	363,6475556	2013,016956	3606,102352	1976,096459	169,4653333	0	7978,226831	5162,958039	14050,2778	5162,958039	0	0	150,1018249	0	16905,5466
2027-02	363,6475556	2013,016956	3606,102352	1976,096459	169,4653333	0	7978,226831	5162,958039	16905,5466	5162,958039	0	0	150,1018249	0	17199,74039
2027-03	363,6475556	2013,016956	3606,102352	1976,096459	169,4653333	0	7978,226831	5162,958039	17199,74039	5162,958039	0	0	150,1018249	0	17493,53418
2027-04	363,6475556	2013,016956	3606,102352	1976,096459	169,4653333	0	7978,226831	5162,958039	17493,53418	5162,958039	0	0	150,1018249	0	17788,12797
2027-05	363,6475556	2013,016956	3606,102352	1976,096459	169,4653333	0	7978,226831	5162,958039	17788,12797	5162,958039	0	0	150,1018249	0	18082,32176
2027-06	363,6475556	2013,016956	3606,102352	1976,096459	169,4653333	0	7978,226831	5162,958039	18082,32176	5162,958039	0	0	150,1018249	0	18376,51556
2027-07	363,6475556	2013,016956	3606,102352	1976,096459	169,4653333	0	7978,226831	5162,958039	18376,51556	5162,958039	0	0	150,1018249	0	18670,70935
2027-08	363,6475556	2013,016956	3606,102352	1976,096459	169,4653333	0	7978,226831	5162,958039	18670,70935	5162,958039	0	0	150,1018249	0	18964,90314
2027-09	363,6475556	2013,016956	3606,102352	1976,096459	169,4653333	0	7978,226831	5162,958039	18964,90314	5162,958039	0	0	150,1018249	0	19259,09693
2027-10	363,6475556	2013,016956	3606,102352	1976,096459	169,4653333	0	7978,226831	5162,958039	19259,09693	5162,958039	0	0	150,1018249	0	19553,29073
2027-11	363,6475556	2013,016956	3606,102352	1976,096459	169,4653333	0	7978,226831	5162,958039	19553,29073	5162,958039	0	0	150,1018249	0	19847,48452
2027-12	363,6475556	2013,016956	3606,102352	1976,096459	169,4653333	0	7978,226831	5162,958039	19847,48452	5162,958039	0	0	150,1018249	0	20141,67831
2028-01	359,1909899	1906,408229	4180,555442	1794,375449	338,6382222	0	8078,843801	7684,033039	20141,67831	7684,033039	0	0	500,324532	0	20536,48907
2028-02	359,1909899	1906,408229	4180,555442	1794,375449	338,6382222	0	8078,843801	8200,609426	20536,48907	8200,609426	0	0	500,324532	0	20414,72345
2028-03	359,1909899	1906,408229	4180,555442	1794,375449	338,6382222	0	8078,843801	8200,609426	20414,72345	8200,609426	0	0	500,324532	0	20292,95782
2028-04	359,1909899	1906,408229	4180,555442	1794,375449	338,6382222	0	8078,843801	8200,609426	20292,95782	8200,609426	0	0	500,324532	0	20171,19219
2028-05	359,1909899	1906,408229	4180,555442	1794,375449	338,6382222	0	8078,843801	8200,609426	20171,19219	8200,609426	0	0	500,324532	0	20049,42656
2028-06	359,1909899	1906,408229	4180,555442	1794,375449	338,6382222	0	8078,843801	8200,609426	20049,42656	8200,609426	0	0	500,324532	0	19927,66094
2028-07	359,1909899	1906,408229	4180,555442	1794,375449	338,6382222	0	8078,843801	8200,609426	19927,66094	8200,609426	0	0	500,324532	0	19805,89531
2028-08	359,1909899	1906,408229	4180,555442	1794,375449	338,6382222	0	8078,843801	8200,609426	19805,89531	8200,609426	0	0	500,324532	0	19684,12968
2028-09	359,1909899	1906,408229	4180,555442	1794,375449	338,6382222	0	8078,843801	8200,609426	19684,12968	8200,609426	0	0	500,324532	0	19562,36406
2028-10	359,1909899	1906,408229	4180,555442	1794,375449	338,6382222	0	8078,843801	8200,609426	19562,36406	8200,609426	0	0	500,324532	0	19440,59843
2028-11	359,1909899	1906,408229	4180,555442	1794,375449	338,6382222	0	8078,843801	8200,609426	19440,59843	8200,609426	0	0	500,324532	0	19318,8328
2028-12	359,1909899	1906,408229	4180,555442	1794,375449	338,6382222	0	8078,843801	8200,609426	19318,8328	8200,609426	0	0	500,324532	0	19197,06718
2029-01	414,134101	1868,188038	4006,617728	1676,131449	214,9777778	0	7518,594531	8200,609426	19197,06718	8200,609426	0	0	661,4545637	0	18515,05228
2029-02	414,134101	1868,188038	4006,617728	1676,131449	214,9777778	0	7518,594531	9290,214586	18515,05228	9290,214586	0	0	661,4545637	0	16743,43222
2029-03	414,134101	1868,188038	4006,617728	1676,131449	214,9777778	0	7518,594531	9290,214586	16743,43222	9290,214586	0	0	661,4545637	0	14971,81217
2029-04	414,134101	1868,188038	4006,617728	1676,131449	214,9777778	0	7518,594531	9290,214586	14971,81217	9290,214586	0	0	661,4545637	0	13200,19211
2029-05	414,134101	1868,188038	4006,617728	1676,131449	214,9777778	0	7518,594531	9290,214586	13200,19211	9290,214586	0	0	661,4545637	0	11428,57206
2029-06	414,134101	1868,188038	4006,617728	1676,131449	214,9777778	0	7518,594531	9290,214586	11428,57206	9290,214586	0	0	661,4545637	0	9656,952002
2029-07	414,134101	1868,188038	4006,617728	1676,131449	214,9777778	0	7518,594531	9290,214586	9656,952002	9290,214586	0	0	661,4545637	0	7885,3391846
2029-08	414,134101	1868,188038	4006,617728	1676,131449	214,9777778	0	7518,594531	9290,214586	7885,3391846	9290,214586	1404,88284	0	661,4545637	0	6145,45637
2029-09	414,134101	1868,188038	4006,617728	1676,131449	214,9777778	0	7518,594531	9290,214586	6145,						

Appendix R Storage Demand Non-Standardised Materials under Combined Adjustments

Under Realistic Reuse Rates

MONTH	CURRENT STORAGE DEMAND (TOTAL)	ACTUAL FLATTENED STORAGE DEMAND (TOTAL)	MAXIMUM FLATTENED STORAGE DEMAND (TOTAL)
2025-01	3953,590789	3962,207749	5650,700946
2025-02	3965,046951	3962,207749	5650,700946
2025-03	3976,503114	3962,207749	5650,700946
2025-04	3987,959277	3962,207749	5650,700946
2025-05	3999,415439	3962,207749	5650,700946
2025-06	4010,871602	3962,207749	5650,700946
2025-07	4022,327765	3962,207749	5650,700946
2025-08	4033,783927	3962,207749	5650,700946
2025-09	4045,24009	3962,207749	5650,700946
2025-10	4056,696253	3962,207749	5650,700946
2025-11	4068,152415	3962,207749	5650,700946
2025-12	4079,608578	3962,207749	5650,700946
2026-01	4555,563745	4421,680193	5650,700946
2026-02	4418,089793	4421,680193	5650,700946
2026-03	4418,089793	4421,680193	5650,700946
2026-04	4418,089793	4421,680193	5650,700946
2026-05	4418,089793	4421,680193	5650,700946
2026-06	4418,089793	4421,680193	5650,700946
2026-07	4418,089793	4421,680193	5650,700946
2026-08	4418,089793	4421,680193	5650,700946
2026-09	4418,089793	4421,680193	5650,700946
2026-10	4418,089793	4421,680193	5650,700946
2026-11	4418,089793	4421,680193	5650,700946
2026-12	4418,089793	4421,680193	5650,700946
2027-01	6783,21094	6786,80134	5650,700946
2027-02	6783,21094	6786,80134	5650,700946
2027-03	6783,21094	6786,80134	5650,700946
2027-04	6783,21094	6786,80134	5650,700946
2027-05	6783,21094	6786,80134	5650,700946
2027-06	6783,21094	6786,80134	5650,700946
2027-07	6783,21094	6786,80134	5650,700946
2027-08	6783,21094	6786,80134	5650,700946
2027-09	6783,21094	6786,80134	5650,700946
2027-10	6783,21094	6786,80134	5650,700946
2027-11	6783,21094	6786,80134	5650,700946
2027-12	6783,21094	6786,80134	5650,700946
2028-01	6868,735364	6863,899808	5650,700946
2028-02	6868,735364	6863,899808	5650,700946
2028-03	6868,735364	6863,899808	5650,700946
2028-04	6868,735364	6863,899808	5650,700946
2028-05	6868,735364	6863,899808	5650,700946
2028-06	6868,735364	6863,899808	5650,700946
2028-07	6868,735364	6863,899808	5650,700946
2028-08	6868,735364	6863,899808	5650,700946
2028-09	6868,735364	6863,899808	5650,700946
2028-10	6868,735364	6863,899808	5650,700946
2028-11	6868,735364	6863,899808	5650,700946
2028-12	6868,735364	6863,899808	5650,700946
2029-01	6392,523485	6388,933085	5650,700946
2029-02	6392,523485	6388,933085	5650,700946
2029-03	6392,523485	6388,933085	5650,700946
2029-04	6392,523485	6388,933085	5650,700946
2029-05	6392,523485	6388,933085	5650,700946
2029-06	6392,523485	6388,933085	5650,700946
2029-07	6392,523485	6388,933085	5650,700946
2029-08	6392,523485	6388,933085	5650,700946
2029-09	6392,523485	6388,933085	5650,700946
2029-10	6392,523485	6388,933085	5650,700946
2029-11	6392,523485	6388,933085	5650,700946
2029-12	6392,523485	6388,933085	5650,700946
2030-01	5413,590246	5409,999846	5650,700946
2030-02	5413,590246	5409,999846	5650,700946
2030-03	5413,590246	5409,999846	5650,700946
2030-04	5413,590246	5409,999846	5650,700946
2030-05	5413,590246	5409,999846	5650,700946
2030-06	5413,590246	5409,999846	5650,700946
2030-07	5413,590246	5409,999846	5650,700946
2030-08	5413,590246	5409,999846	5650,700946
2030-09	5413,590246	5409,999846	5650,700946
2030-10	5413,590246	5409,999846	5650,700946
2030-11	5413,590246	5409,999846	5650,700946
2030-12	5413,590246	5409,999846	5650,700946

Under Theoretic Reuse Rates

MONTH	CURRENT STORAGE DEMAND (TOTAL)	ACTUAL FLATTENED STORAGE DEMAND (TOTAL)	MAXIMUM FLATTENED STORAGE DEMAND (TOTAL)
2025-01	4651,283281	4661,420881	13006,7778
2025-02	5360,431936	5305,640469	13006,7778
2025-03	6069,58059	5949,860057	13006,7778
2025-04	6778,729245	6594,079645	13006,7778
2025-05	7487,8779	7238,299233	13006,7778
2025-06	8197,026555	7882,518821	13006,7778
2025-07	8906,17521	8526,73841	13006,7778
2025-08	9615,323864	9170,957998	13006,7778
2025-09	10324,47252	9815,177586	13006,7778
2025-10	11033,62117	10459,39717	13006,7778
2025-11	11742,76983	11103,61676	13006,7778
2025-12	12451,91848	11747,83635	13006,7778
2026-01	13707,53656	12932,61176	13006,7778
2026-02	13742,33121	12971,63041	13006,7778
2026-03	13777,12587	13010,64907	13006,7778
2026-04	13811,92053	13049,66773	13006,7778
2026-05	13846,71519	13088,68639	13006,7778
2026-06	13881,50985	13127,70505	13006,7778
2026-07	13916,30451	13166,72371	13006,7778
2026-08	13951,09917	13205,74237	13006,7778
2026-09	13985,89383	13244,76103	13006,7778
2026-10	14020,68849	13283,77969	13006,7778
2026-11	14055,48314	13322,79834	13006,7778
2026-12	14090,2778	13361,817	13006,7778
2027-01	16905,5466	14477,70158	13006,7778
2027-02	17199,74039	14776,11937	13006,7778
2027-03	17493,93418	15074,53716	13006,7778
2027-04	17788,12797	15372,95495	13006,7778
2027-05	18082,32176	15671,37274	13006,7778
2027-06	18376,51556	15969,79054	13006,7778
2027-07	18670,70935	16268,20833	13006,7778
2027-08	18964,90314	16566,62612	13006,7778
2027-09	19259,09693	16865,04391	13006,7778
2027-10	19553,29073	17163,46171	13006,7778
2027-11	19847,48452	17461,8795	13006,7778
2027-12	20141,67831	17760,29729	13006,7778
2028-01	20536,48907	18149,41916	13006,7778
2028-02	20414,72345	18021,96465	13006,7778
2028-03	20292,95782	17820,9973	13006,7778
2028-04	20171,19219	16173,96695	13006,7778
2028-05	20049,42656	14526,9366	13006,7778
2028-06	19927,66094	12879,90626	13006,7778
2028-07	19805,89531	11232,87591	13006,7778
2028-08	19684,12968	9585,845564	13006,7778
2028-09	19562,36406	7938,815218	13006,7778
2028-10	19440,59843	6553,579081	13006,7778
2028-11	19318,8328	6553,579081	13006,7778
2028-12	19197,06718	6553,579081	13006,7778
2029-01	18515,05228	5904,090619	13006,7778
2029-02	16743,43222	6418,338635	13006,7778
2029-03	14971,81217	6418,338635	13006,7778
2029-04	13200,19211	6418,338635	13006,7778
2029-05	11428,57206	6418,338635	13006,7778
2029-06	9656,952002	6418,338635	13006,7778
2029-07	7885,331946	6418,338635	13006,7778
2029-08	7518,594531	6418,338635	13006,7778
2029-09	7518,594531	6418,338635	13006,7778
2029-10	7518,594531	6418,338635	13006,7778
2029-11	7518,594531	6418,338635	13006,7778
2029-12	7518,594531	6418,338635	13006,7778
2030-01	6366,908368	5825,436853	13006,7778
2030-02	6366,908368	6362,684368	13006,7778
2030-03	6366,908368	6362,684368	13006,7778
2030-04	6366,908368	6362,684368	13006,7778
2030-05	6366,908368	6362,684368	13006,7778
2030-06	6366,908368	6362,684368	13006,7778
2030-07	6366,908368	6362,684368	13006,7778
2030-08	6366,908368	6362,684368	13006,7778
2030-09	6366,908368	6362,684368	13006,7778
2030-10	6366,908368	6362,684368	13006,7778
2030-11	6366,908368	6362,684368	13006,7778
2030-12	6366,908368	6362,684368	13006,7778

