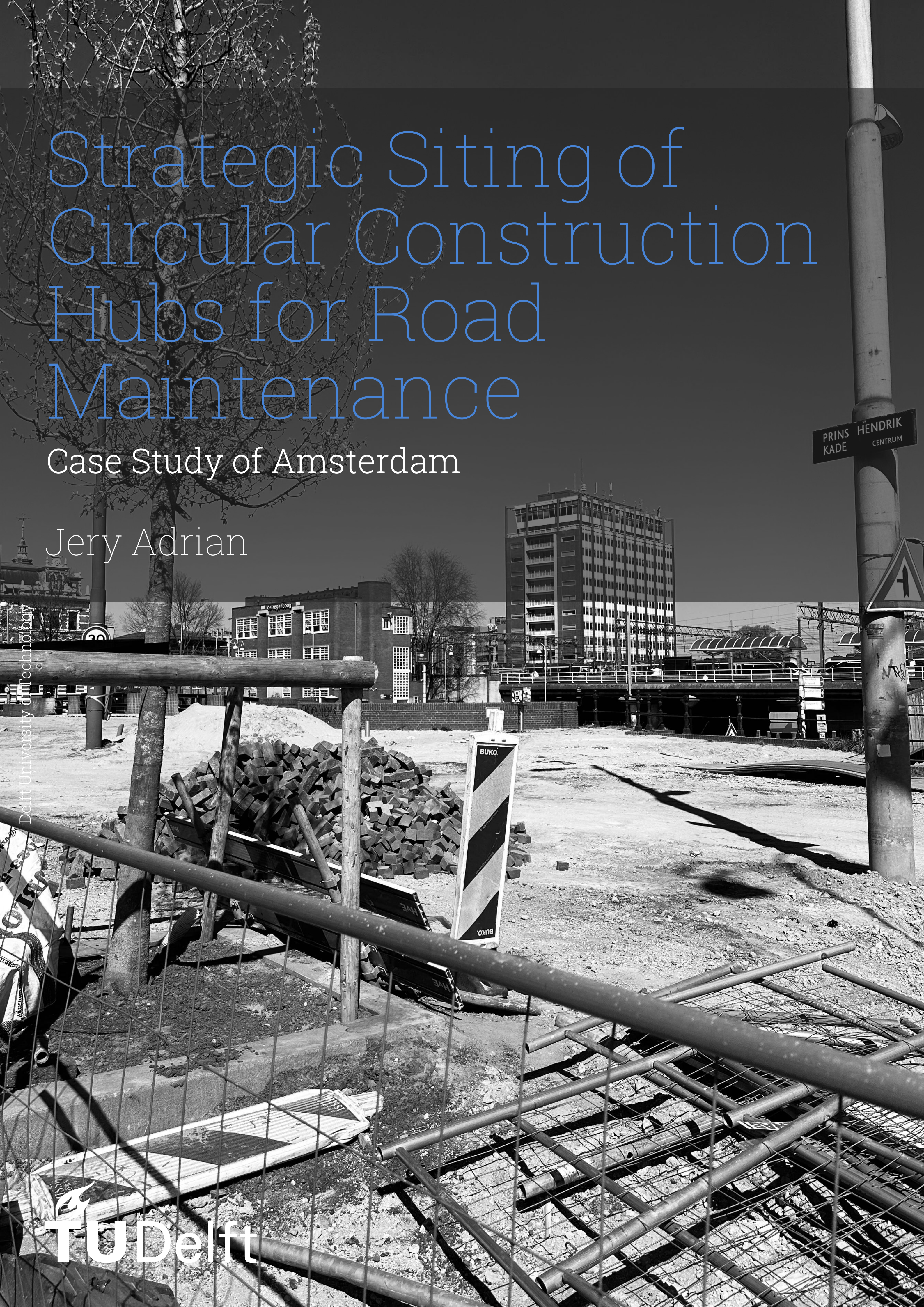
Strategic Siting of Circular Construction Hubs for Road Maintenance

Case Study of Amsterdam

Jery Adrian



Delft University of Technology

TU Delft

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by

Jery Adrian

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Preface

My journey into this research began with a fascination for a simple yet powerful idea: that the waste from today's cities could become the resource for tomorrow's. The challenge, I quickly learned, lies not in the vision but in the logistics. How do we create a system that is not only circular in principle, but also efficient, economical, and practical on the ground? This thesis is my attempt to answer a small part of that question.

This intellectual journey was not one I took alone. I am deeply grateful to my supervisory team for helping me navigate the complexities of this topic: my chairperson, Eleni Papadonikolaki, whose role as chair was instrumental in guiding the overall writing of this thesis; my first supervisor, Ruben Vrijhoef, for his expert guidance in transforming a broad vision into a rigorous academic study; and my second supervisor, Petar Koljensic, who provided invaluable support on the technical aspects of the spatial analysis. I would also like to extend my sincere thanks to Felix Fröhling, who, although not a member of my committee, introduced me to this thesis topic and generously shared his deep insights on circularity in road maintenance in Amsterdam.

A special thank you is owed to the professionals who shared their time and expertise. Your insights into the realities of road maintenance and material flows were invaluable and ensured this project remained connected to the real-world challenges it seeks to address.

Of course, no academic work is completed in a vacuum. I thank my friends and colleagues for the moments of levity and support. Most importantly, I thank my family for their endless patience and belief in me.

I present this work with the hope that its findings may be of some value to planners and policymakers working to build the resilient, circular cities of the future.

Jery Adrian
Delft, August 2025

Summary

The construction industry is a major contributor to global carbon emissions, creating an urgent need to adopt circular economy principles. While cities such as Amsterdam have set ambitious circularity targets, the high-value reuse of construction materials is often hindered by a gap between policy ambition and logistical realities. This thesis addresses this gap by asking: *How can Circular Construction Hubs (CCHs) be strategically located and configured to support material reuse in urban road maintenance?*

The research framework combines quantitative modeling with qualitative validation. A data-driven process based on the Design Science Research Methodology (DSRM) was used to model and optimize logistics networks. This included a GIS-based suitability analysis to identify potential hub locations and a custom heuristic algorithm to refine network configurations. The performance of Centralized, Decentralized, and Hub-and-Spoke models was evaluated in terms of total transport effort, measured in tonne-kilometers (t-km). These optimized models were then assessed for feasibility through semi-structured interviews with municipal, industry, and academic experts to ensure the recommendations reflect practical constraints and operational realities.

The analysis highlights a core strategic trade-off. A refined 5-CCH Decentralized network proved the most transport-efficient, reducing total t-km by 32 percent compared to the baseline by aligning hubs with material hotspots. In contrast, a refined 6-TSS Hub-and-Spoke network incurred 22 percent higher transport effort but delivered stronger operational resilience, offering a two-tiered structure to manage complex logistics and meet regulatory requirements such as Zero-Emission Zones.

Synthesizing these findings with expert insights on spatial scarcity and operational complexity, the thesis concludes that no single model is sufficient. Instead, it proposes a scalable hybrid framework that integrates three tiers: (1) permanent, demand-driven CCHs as core processing hubs, (2) flexible TSSs to strengthen resilience and manage regional flows, and (3) temporary staging areas to enable short-term, hyper-local reuse. This demand-driven approach provides planners with a practical blueprint for logistics networks that can translate circular economy principles into operational reality.

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1 Introduction

1.1. Background

The construction industry is a major contributor to global CO_2 emissions, accounting for approximately 34% of global energy demand and 37% of energy-related CO_2 emissions (UNEP and GlobalABC, 2024). Despite nearly 90% of construction materials being recycled, high-value reuse remains limited because most materials are downcycled into aggregates rather than repurposed for new projects (Circle Economy and Metabolic, 2022). This paradox is particularly evident in the realm of road infrastructure, which is not only essential for urban connectivity but also a significant source of emissions. In the Netherlands, roads and pavements contribute 68% of infrastructure-related emissions, amounting to 2723 kiloton CO_2-eq per year (Arnoldussen et al., 2022).

In response to these challenges, the Dutch government has set an ambitious goal of achieving a fully circular built environment by 2050. This vision emphasizes reducing material extraction and maximizing reuse through urban mining strategies (Rijksoverheid, 2019). For cities like Amsterdam, which aims to reduce CO_2 emissions by 60% by 2030, this objective is especially critical. However, current projections reveal a significant shortfall; anticipated emission reductions range from only 15% under minimal policy scenarios to 56% under maximum implementation measures (City of Amsterdam, 2023). These discrepancies underscore the urgent need for more effective strategies to manage material flows and enhance recycling practices.

Circular systems offer a promising pathway by extending the lifecycle of materials and reducing reliance on virgin resources. In particular, concrete tiles and bricks, which are commonly used in road construction, have high reuse potential (Fröhling, 2023; Küpfer et al., 2022). Their high-value reuse could substantially lower both material extraction and CO_2 emissions, thereby advancing broader circular economy objectives. Yet, despite their promise, practical implementation faces considerable challenges. Research by Holly et al. (2023) highlights barriers such as limited financial support, inadequate infrastructure for processing secondary materials, and supply chain inefficiencies. Furthermore, the complexity of coordinating material flows is compounded by regulatory uncertainties and the restricted availability of suppliers, ultimately leading to inefficient material management practices that drive up transportation costs and result in underutilized infrastructure.

1.2. Problem Definition

The Circular Construction Hub (CCH) has emerged as a solution to address inefficiencies in material reuse by consolidating, storing, and redistributing secondary construction materials. While these large, permanent hubs form the foundation of a circular logistics network, their effectiveness can be enhanced by a multi-layer system that also includes smaller, agile facilities. This thesis will refer to these smaller, local consolidation points as Temporary Storage Sites (TSS). By acting as logistical nodes within this two-tiered network, these hubs could improve spatial connectivity between material suppliers and construction sites while reducing transport distances and overall environmental impact (Köhrer, 2024). This improvement paves the way for a greater adoption of secondary materials, a shift that could lead to significant reductions in carbon emissions (Nußholz et al., 2019).

While CCH and its supporting networks offer environmental benefits, their adoption is hindered by economic feasibility, policy support, and logistical challenges (Mhatre et al., 2021; Munaro and Tavares, 2023; Van der Mark, 2024). Secondary materials often struggle to compete with virgin alternatives due to pricing mechanisms that do not account for embedded carbon savings. Without financial incentives or taxation on virgin materials, reused materials remain economically disadvantaged while uncertainties in demand and supply chains continue to limit large-scale implementation. Moreover, mismatches between supply and demand and arbitrarily placed hubs risk increasing transport inefficiencies rather than reducing them, particularly in dense urban areas where transport costs and storage constraints further complicate operations (Espinoza et al., 2020; Joensuu et al., 2020; Van Uden et al., 2025).

Given these challenges, the effectiveness of CCH is strongly dependent on spatial configuration; hub placement directly influences transport efficiency, resource accessibility, and overall logistical feasibility. Recent research has increasingly employed spatial methodologies to investigate these interdependencies. Tsui et al. (2023) identified key spatial parameters influencing hub placement, incorporating factors such as resource availability, accessibility, land use, and socioeconomic conditions. Shan (2023) applied GIS and Material Flow Analysis (MFA) to assess urban mining potential and optimize hub locations for circular building materials, emphasizing circular logistics and material recovery strategies. Yang et al. (2023) further integrated building stock models with logistics networks to analyze how secondary material flows align with hub siting, considering both forward and reverse logistics impacts. Tsui et al. (2024) advanced this work by employing spatial optimization techniques to determine the optimal number and distribution of timber hubs in the Amsterdam Metropolitan Area.

Although previous research has identified suitable locations for circular construction hubs, there is a notable gap in exploring how different hub configurations impact operational efficiency. Existing research typically relies on ad hoc hub placements and have not comprehensively evaluated the spatial, logistical, and economic factors that are unique to road maintenance. This oversight is critical because inefficient hub configurations can lead to increased transport costs, mismatches in supply and demand, and underutilized infrastructure, ultimately impeding the broader adoption of circular economy practices in urban environments.

Therefore, this thesis aims to fill that gap by developing a structured GIS analysis that evaluates various hub configuration models to optimize material reuse and enhance logistical connectivity. Specifically, this thesis will focus on concrete tiles and bricks as road maintenance materials because of their high potential and constitute more than 70% of the total materials required for projects between 2025 and 2030 (internal data). Using Amsterdam as a case study, the ultimate goal of this thesis is to provide practical guidance that can be adapted for use in diverse urban contexts.

1.3. Research Objectives

In line with Amsterdam's climate targets and the need to strategically assess the placement of Circular Construction Hub (CCH) for concrete tiles and bricks in urban road maintenance, this thesis aims to develop a decision-making framework that evaluates both spatial and logistical factors in CCH location and configuration. Specifically, this thesis will:

1. Develop a data-driven framework for identifying and evaluating potential locations for a multi-tiered network of Circular Construction Hubs (CCHs) and Temporary Storage Sites (TSSs), integrating GIS-based suitability criteria with real-world material flow data.
2. Model and quantitatively evaluate the performance of different network configurations (e.g., Centralized, Decentralized, Hub-and-Spoke) to identify the fundamental strategic trade-off between transport efficiency and operational flexibility.
3. Demonstrate an iterative, DSRM-based process for refining an initial network design, using a custom-developed heuristic algorithm to resolve identified inefficiencies and produce quantitatively superior network models.
4. Synthesize quantitative findings with qualitative expert insights to assess the real-world feasibility of the proposed networks and to derive a set of transferable, strategic principles for the planning of circular logistics infrastructure in other cities.

1.4. Research Questions

To fulfill these objectives, the thesis is guided by one overarching main research question and three sub-research questions as follows:

> *"How can Circular Construction Hubs be strategically located and configured to support material reuse in urban road maintenance?"*

In order to answer the main RQ stated above, the following sub-research questions (Sub-RQs) are formulated:

Sub-RQ1: *"What are the key criteria for CCH location and how can relevant data be utilized to identify candidate locations?"*

Sub-RQ2: *"How can different CCH configurations be evaluated, and how do variations in assumptions impact their effectiveness?"*

Sub-RQ3: *"What key decision-making insights from this thesis can support the planning of CCH in other cities?"*

1.5. Research Scope

This study's scopes are defined by its specific focus, its distinct methodological approach, and its potential contribution to both academic discourse and practical urban planning.

Geographical

The geographical scope of this research is the City of Amsterdam. This choice is strategic, as Amsterdam represents a compelling case study due to its ambitious circularity policies, the availability of granular municipal data on road maintenance, and its dense urban structure, which presents acute logistical challenges. This focus allows for a detailed spatial analysis that captures the influence of local policy, infrastructure, and material flows, ensuring the research outcomes are grounded in a real-world context.

Material

The material focus of this research is on the reverse logistics of secondary concrete tiles and bricks generated from road maintenance projects in Amsterdam. These materials were chosen because they represent a significant, high-volume stream within the city's maintenance activities. Additionally, they offer strong potential for direct, high-value reuse without requiring extensive reprocessing. Their standardized characteristics further enhance their suitability for modeling and logistical planning within the scope of this thesis.

Methodological

The methodological scope of this thesis centers on the design and evaluation of a multi-layer circular logistics network. Rather than focusing solely on the identification of individual hubs, the research extends to configuring an integrated system that includes two distinct facility types: Circular Construction Hubs (CCH), which are larger, permanent facilities for sorting, processing, and storage, and Temporary Storage Sites (TSS), which serve as smaller, flexible consolidation points functioning as "spokes" within the network. The analysis assesses the performance of three network configurations: Centralized, Decentralized, and Hub-and-Spoke, using a quantitative, data-driven approach. Total system tonne-kilometers (t-km), a standard industry metric that serves as a proxy for transport costs and associated carbon emissions, is used as the primary analytical measure. The entire analysis is carried out within a Design Science Research (DSRM) framework, employing an iterative process of design, demonstration, and evaluation to progressively refine the network models.

1.6. Relevance

The relevance of this research lies in its potential to bridge the critical gap between high-level circular economy ambitions and the practical logistical planning required to realize them. Its contributions consist of three key aspects:

1. **Transferable Framework for Strategic Siting:**
Beyond the specific results for Amsterdam, this thesis offers a replicable, demand-driven methodology that other cities could adapt. It demonstrates how to move from a conventional land-use-first approach to a more effective demand-centric model for locating circular infrastructure, ensuring that investments are targeted where they can deliver the greatest logistical benefit.
2. **Fundamental Strategic Trade-Off:**
The research makes a crucial contribution by quantitatively modeling the trade-off between a transport-efficient Decentralized network and an operationally resilient Hub-and-Spoke network. This provides policymakers with a clear, evidence-based framework for making a strategic choice that aligns with their city's specific priorities, whether they be minimizing carbon emissions or managing complex urban logistics and regulatory constraints.
3. **Regulatory and Operational Challenges:**
The findings are directly relevant to the increasing number of cities implementing Low or Zero-Emission Zones (ZEZs). The Hub-and-Spoke model, with its network of TSSs, offers a practical, future-proofed solution for managing last-mile logistics in restricted urban cores. This elevates the relevance of the research from a purely circular economy issue to a key enabler of broader urban sustainability and climate goals.

1.7. Research Outline

This thesis is structured as follows:

- **Chapter 2:**
Establishes the theoretical framework for this study. It reviews the principles of the Circular Economy within the construction sector, examines secondary material flows in road infrastructure, and details the concept, evolution, and typologies of CCH. The chapter concludes by establishing the Amsterdam case study, connecting its circularity policies and the material standardization enabled by the Puccini Method to the scale and nature of upcoming road maintenance material flows.
- **Chapter 3:**
Describes the research methodology adopted to investigate the strategic location and configuration of CCHs. This section details the multi-phase methodology, guided by the Design Science Research (DSRM) framework. This section outlines the GIS-based suitability analysis for identifying candidate CCH and TSS locations, the network configuration models (Centralized, Decentralized, and Hub-and-Spoke), and the custom-developed Greedy Heuristic algorithm used for iterative network optimization.
- **Chapter 4:**
Presents the quantitative findings by following the iterative DSRM cycle. It begins by evaluating the inefficient performance of an initial network design, diagnosing key bottlenecks and service gaps. It then details the redesign process and presents the significantly improved results of the refined configurations, quantifying the gains in logistical efficiency and demonstrating the value of the iterative approach.
- **Chapter 5:**
Provides an in-depth discussion of the research findings, focusing on the fundamental strategic trade-off between the transport-efficient Decentralized model and the operationally resilient Hub-and-Spoke model. It synthesizes the results into transferable strategic principles for facility siting and evaluates the practical feasibility of the proposed networks within the Amsterdam context, drawing on policy analysis and expert insights.
- **Chapter 6:**
Concludes the thesis by summarizing the key findings, providing concise answers to the research questions, and highlighting the thesis's primary contributions to the theory and practice of circular construction logistics.

2 Theoretical Framework

2.1. Overview

This chapter provides the theoretical and contextual foundation needed to address the research question. It moves from broad foundational concepts to the specific context of the case study. The chapter first introduces the core principles of the Circular Economy (CE) and its hierarchical strategies within the construction sector. It then focuses on secondary material flows in road infrastructure, identifying key materials and the barriers that limit high-value reuse.

In response to these barriers, the chapter explores the Circular Construction Hub (CCH) as a strategic solution, examining its typologies, core functions, and the facility-location theories that guide its placement. The related concept of the smaller, more agile Temporary Storage Site (TSS) is then defined and discussed. Finally, the chapter grounds these theories in the specific context of Amsterdam, describing its circularity policies, material standardization practices, and upcoming road maintenance data that serve as the input for the research model. Together, these sections provide the groundwork for the methodology and analysis in the following chapters.

2.2. Circular Economy in the Construction Sector

The concept of Circular Economy (CE) has its roots in the 1960s and 1970s, drawing from ideas in industrial ecology, which views industrial systems as analogous to natural ecosystems where waste is repurposed as input for new production processes (Ghisellini et al., 2016). Among the key figures shaping CE, Walter R. Stahel is widely recognized as a pioneer for his work in extending product lifecycle. In 1982, he introduced the concept of the "Product-Life Factor," emphasizing reuse, repair, and remanufacturing as strategies to minimize waste and improve resource efficiency. Stahel's work laid the groundwork for modern CE principles. In 21st century, the Ellen MacArthur Foundation has been instrumental in shaping CE principles globally through development of the CE framework and actionable corporate strategies (Ellen MacArthur Foundation, 2013).

Today, CE is recognized as a system that seeks to minimize resource inputs, waste generation, emissions, and energy losses by implementing strategies that slow, close, and narrow material and energy loops. This approach is realized through practices such as durable design, maintenance, repair, reuse, re-manufacturing, refurbishing, and recycling (Geissdoerfer et al., 2017). As seen in 2.1, Circle Economy and Metabolic (2022) propose four complementary strategies for impact: "narrow" (improve material efficiency), "cycle" (reprocess and reuse materials), "regenerate" (strengthen the circularity of biomass and reduce the footprint of non-renewables), and "slow" (extend product and building lifetimes).

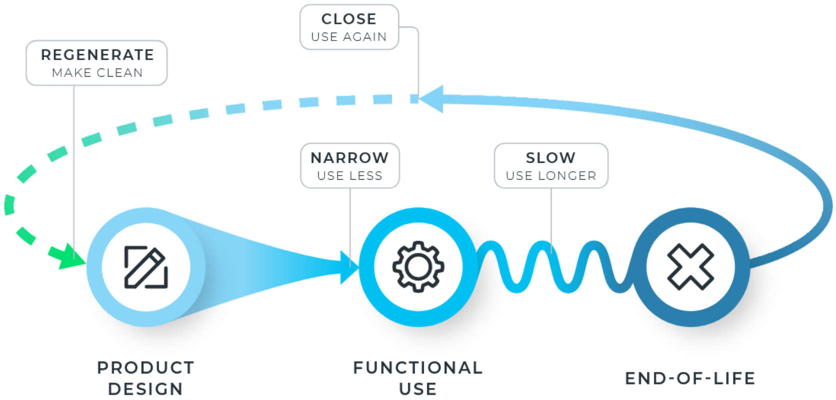


Figure 2.1: Four flows to achieve circular objectives (Circle Economy and Metabolic, 2022).

In the construction sector, which accounts for a significant share of global resource consumption and waste generation, adopting CE principles has been widely recognized as a critical step in mitigating environmental impacts. As one of the most material-intensive industries, construction presents significant opportunities to implement circular strategies by treating construction and demolition waste (C&DW) as a secondary resource rather than landfill-bound waste. The application of CE principles in construction primarily focuses on extending material lifespans and reducing reliance on virgin resources. For example, cycling materials in road infrastructure or slowing material flows by extending the service life of concrete components can meaningfully lower emissions and raw material consumption.

Furthermore, a more structured approach to circularity has been established through hierarchical strategies known as the ”10Rs” framework (Potting et al., 2017). These strategies, ranging from R0 (Refuse) to R9 (Recover), outline a priority-based system for material retention in the economy. As shown in Figure 2.2, higher-priority strategies (R0-R3) aim to prevent waste generation altogether, while lower-priority strategies (R7-R9) involve material recovery and recycling, which often lead to downcycling.

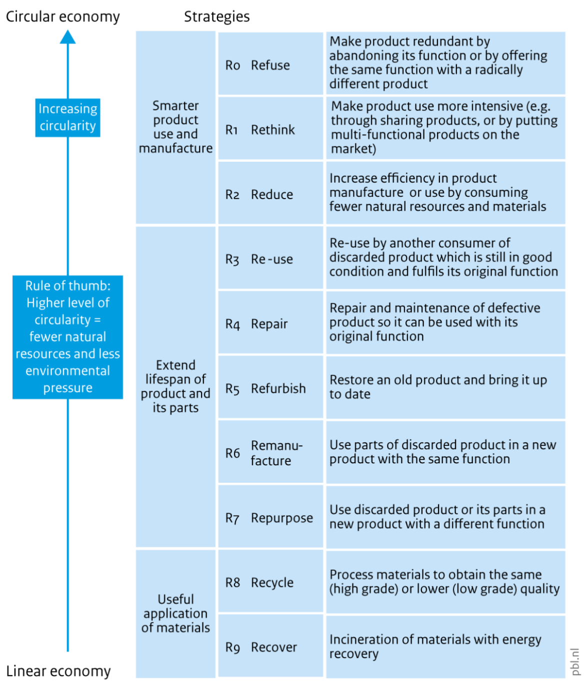


Figure 2.2: 10Rs strategies (Potting et al., 2017).

Potting et al. (2017) further emphasized that the most desirable strategies, such as R0 (Refuse) and

R1 (Reduce), focus on reducing resource consumption through improved efficiency and product design. Conversely, lower-priority strategies, such as R7 (Recycle) and R8-R9 (Energy Recovery), involve higher energy inputs and result in lower material retention value.

Reike et al. (2018) expanded upon this concept by proposing a 10Rs typology of resource value retention options. They further categorized the 10Rs into three distinct loops based on their degree of circularity and impact on resource retention:

- Short loops (RO-R3) - closest to the consumer and generally provide the highest level of resource retention.
- Medium loops (R4-R6) - involves upgrading or modifying used products through business or industrial processes, ensuring they retain value for longer.
- Long loops (R7-R9) - deal with more traditional waste management processes that often result in material downcycling.

This hierarchical approach provides a systematic perspective on CE strategies, particularly in the construction sector. Despite the Netherlands achieving nearly 90% recycling rates for C&DW, much of this recycling occurs in long-loop processes, where materials are crushed and repurposed as low-grade aggregates. While this reduces waste disposal, it does not maximize material retention value due to the high energy consumption required for processing and the loss of structural properties. Therefore, a key challenge in construction is shifting from long-loop strategies toward shorter-loop approaches that emphasize direct material reuse and high-value recovery (Reike et al., 2018).

One area of the built environment where short-loop strategies may offer substantial impact is road infrastructure. Roads and pavements are characterized by high material turnover due to recurring maintenance, upgrades, and redesigns, particularly in urban environments. This dynamic creates a steady stream of potentially reusable materials, such as paving stones, curbstones, and concrete tiles. Moreover, road infrastructure offers a geographically contained context where materials can be recovered and reintegrated with minimal processing and transport. As such, the circular economy's abstract principles find tangible opportunities in the planning, maintenance, and material management of urban roads.

2.3. Secondary Material Flows in Road Infrastructure

Building on the principles of the Circular Economy, this section focuses on their application within road infrastructure. Traditionally, material flows in construction have followed a linear model of extraction, use, and disposal. This section examines the transition from this linear paradigm to a circular one, where secondary materials are valued as resources. It contrasts the linear and circular models of material flow in construction, examines the characteristics of secondary materials from road maintenance, identifies key materials such as concrete tiles and bricks with potential for high-value reuse, and outlines the barriers that hinder their widespread adoption.

2.3.1. Material Flows in Construction

Traditionally, material flows in construction have predominantly followed a linear model, in which resources move in a straight path from virgin material extraction to manufacturing, construction, usage, and disposal. This process, often summarized as ”take, make, dispose”, relies on continuous resource input while generating significant waste at the end of structure's lifecycle (Ellen MacArthur Foundation, 2013). The linear model presents challenges at both ends of the system: it depletes finite natural resources while simultaneously increasing landfill waste, which further accelerating environmental degradation

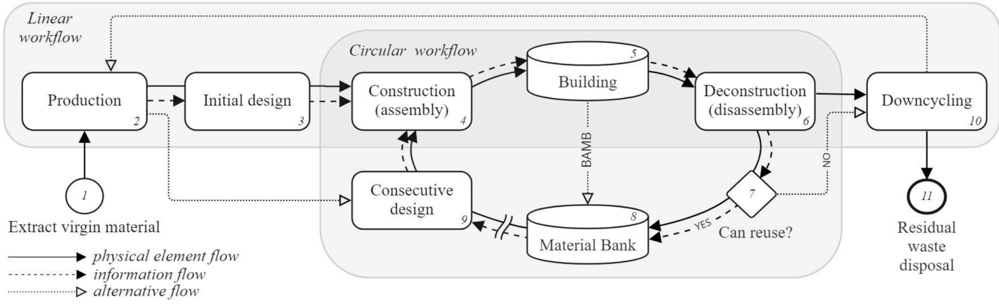


Figure 2.3: Comparison of linear and circular material flows in construction (Tomczak et al., 2023).

In contrast, the circular economy model introduces a closed-loop system that aims to minimize resource depletion and waste generation by retaining materials within the construction cycle for as long as possible. As illustrated in Figure 2.3, circular construction replaces the traditional disposal-oriented approach with 10R strategies from circular economy model. This approach shifts construction from a waste-generating system to a material circulation model, where outgoing materials can follow various recovery pathways instead of being discarded.

While the circular economy model emphasizes keeping materials in use through systemic redesign, it is also essential to consider the practical pathways that outgoing materials can follow at the end of a construction project. Figure 2.4 from Larsson and Gammelsæter (2023) illustrates these post-use strategies in both linear and circular systems, emphasizing how materials are managed after becoming surplus or waste on-site.

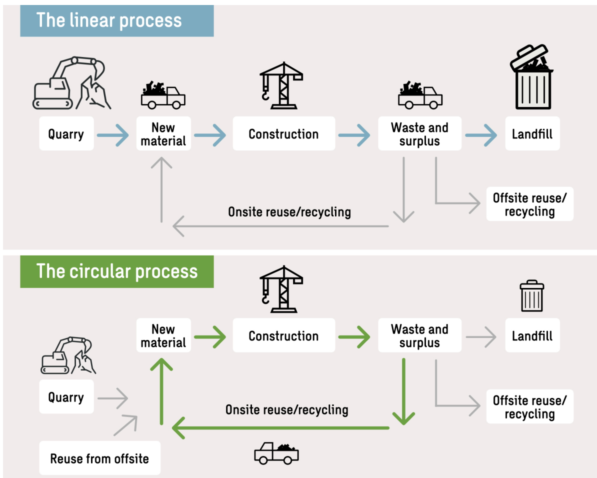


Figure 2.4: Material flow for linear and circular construction (Larsson & Gammelsæter, 2023).

In the linear process, surplus materials are often discarded to landfills with minimal recovery, continuing the "take-make-dispose" model. Circular construction, on the other hand, provides several alternatives:

- Onsite reuse and recycling: materials are directly reintegrated into the current project.
- Offsite reuse and recycling: materials that cannot be reused on-site are sent to external facilities for further processing or redistribution.
- Reuse from offsite sources: incorporate materials recovered from other construction sites.

These recovery routes not only reduce landfill dependency but also promote more sustainable material flows that align with the principles of circular construction. However, the effectiveness of these strategies largely depends on the identification of suitable end-use applications for secondary materials.

Among the various sectors, road infrastructure stands out as a key opportunity, given its capacity to incorporate substantial volumes of reused and recycled materials without compromising performance.

2.3.2. Secondary Materials in Road Maintenance

The European construction industry is characterized by significant material consumption, with maintenance activities accounting for the largest material flows. Of the total 4.3 gigatonnes of material use in the sector, a substantial portion is directed toward maintaining existing infrastructure rather than new construction projects (Kubbinga et al., 2017). This trend reflects a broader shift in the European Union, where road network expansion is gradually slowing, leading to an increasing focus on renewal and maintenance rather than large-scale new developments (European Commission: Joint Research Centre-Institute for Prospective Technological Studies, 2016).

A similar pattern is observed in the Netherlands, where the proportion of material use allocated to new road construction has declined to approximately 30%, with the majority of material flows now directed toward road renewal and maintenance. This shift is expected to continue as existing infrastructure stocks become increasingly saturated, reducing the need for new roads while amplifying the importance of circular material strategies in maintenance operations (Fröhling, 2023).

The Dutch road network is categorized into two main networks: the Main Road Network (MRN) and the Secondary Road Network (SRN). The MRN, managed by *Rijkswaterstaat* (Directorate General for Public Works and Water Management), spans 5,458 kilometers (European Commission: Directorate-General for Mobility and Transport, 2021) and is composed almost entirely of asphalt roads, accounting for approximately 95% of its surface (Welle, 2005). These roads have a multi-layered design, with different layers requiring replacement at varying intervals. In contrast, the SRN, which extends around 134,986 kilometers (European Commission: Directorate-General for Mobility and Transport, 2021) and falls under the jurisdiction of regional and local municipality, features a wider variety of pavement types. While asphalt roads are still common, many SRN roads are paved with bricks or concrete blocks, which offer greater reuse potential compared to asphalt surfaces.

Keijzer et al. (2015) highlight that the maintenance cycles of different road materials significantly influence their potential for reuse. Asphalt roads, particularly those in the MRN, require frequent resurfacing, with porous asphalt surface layers being replaced every 10 to 12 years, while the deeper base layers last for approximately 40 years. SRN asphalt roads, which have a thinner single-layer construction, undergo resurfacing every 20 years. In contrast, brick and concrete paving blocks exhibit substantially longer lifespans, with 90% lasting up to 50 years and only 10% requiring replacement after 25 years.

Given their high potential for reuse, particularly within the Secondary Road Network (SRN) where they are commonly used, these specific materials merit closer examination. Their unique characteristics set them apart from asphalt and highlight their importance in promoting circular practices in road maintenance.

2.3.3. Key Materials

Concrete tiles and bricks play a crucial role in urban road infrastructure, particularly in the Netherlands, where they constitute a significant portion of the Secondary Road Network (SRN). Thom (Thom, 2024) states that these materials fall under the category of block paving in pavement engineering. Unlike rigid pavements, which rely on continuous concrete slabs, block paving consists of small, individual units such as concrete bricks, baked clay bricks, and concrete tiles, laid in an interlocking pattern. This discontinuous structure allows for greater flexibility, easier maintenance, and better load distribution, making block paving a preferred choice for urban streets, pedestrian zones, and historical areas.

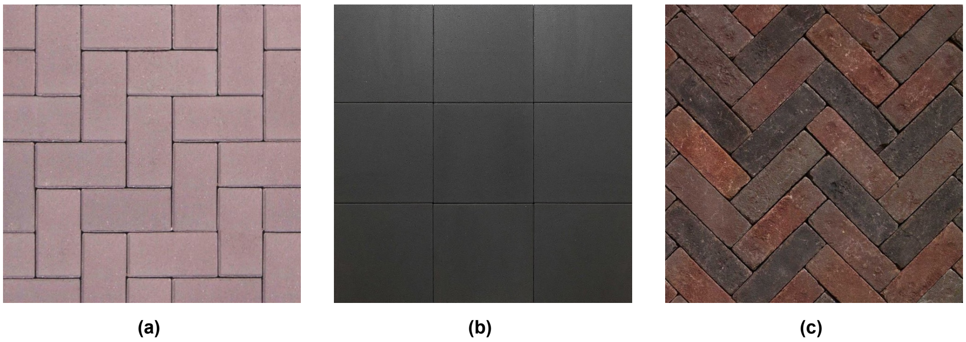


Figure 2.5: Different types of paving stones: (a) *betonsteen*, (b) *betontegel*, (c) *Baksteen* (source: Google Images).

In the Netherlands, block paving is commonly referred to as *elementverharding* (elemental paving) (Gemeente Amsterdam, 2024), which includes *betonsteen* (concrete paving stones), *betontegel* (concrete tiles), and *baksteen* (baked bricks) (Figure 2.5). Even though these materials exhibit the strength and durability of concrete, their discontinuous nature means they do not behave like rigid pavements. Depending on the base layer, block paving can function similarly to flexible pavements in lightly trafficked areas or resemble composite pavements when installed over a rigid foundation (Thom, 2024).

The long lifespan of bricks and concrete paving blocks significantly enhances their potential for reuse. Unlike asphalt, which degrades over time and requires resurfacing or removal, these materials retain their structural integrity for decades. This durability allows for direct reuse, as intact elements can be salvaged, cleaned, sorted, and reinstalled in new road maintenance projects without requiring extensive processing. In contrast, asphalt often undergoes downcycling or energy-intensive recycling, making it less compatible with circular construction strategies. Although asphalt recycling remains the dominant approach in Main Road Networks (MRN) maintenance, the reuse of brick and concrete paving blocks in SRN roads offers a stronger opportunity for circularity.

Circularity in road maintenance depends on effective secondary material flows. Keijzer et al. (2015) highlight that reuse rates for concrete and bricks pavements in Dutch road construction industry are notably high, with up to 90% of concrete elements can be reused after 25 years. If direct reuse is not viable, these materials enter the secondary material stream, where they are crushed into granulates for use as road foundations and sub-bases (Arnoldussen et al., 2022). Recycled concrete granulate is one of the largest secondary material flows in civil engineering, and bricks that cannot be reused are often crushed into breakstone aggregates.

To enhance circularity, innovative method called *Kringbouw* have been developed in the Netherlands, which repurpose concrete waste into secondary raw materials for new paving elements. This method has the potential to reduce primary material use by up to 70% and cut CO_2 emissions in half (Keijzer et al., 2015). Additionally, alternative brick solutions, such as ceramic-waste bricks, are being explored as sustainable substitutes to further minimize environmental impacts (Fröhling, 2023).

The significance of these materials in urban road infrastructure is closely linked to city-level maintenance planning, which will be further explored in 2.6, using Amsterdam as a case study.

2.3.4. Barriers and Challenges

Despite growing recognition of the environmental and economic benefits of secondary material use, several persistent barriers hinder their widespread adoption in road infrastructure. These challenges stem from supply inconsistencies, economic feasibility concerns, regulatory gaps, and logistical inefficiencies, all of which contribute to the limited integration of reused and recycled materials in construction projects.

Supply and Inventory

The availability of secondary materials is unpredictable due to is dependence on deconstruction projects (Köhrer, 2024). Unlike primary materials, which can be produced on demand, the supply of reclaimed construction components is dictated by demolition timelines, leading to irregular material flows and inventory shortages (Van der Mark, 2024). Additionally, there is often limited information about the quality, specifications, and usability of recovered materials, making it difficult for designers and contractors to confidently incorporate them into new projects (Köhrer, 2024). These uncertainties reduce the attractiveness of secondary materials and increase reliance on virgin materials.

Economic and Market

The cost competitiveness of secondary materials remains a major barrier to their adoption. According to Van Uden et al. (2025), circular construction methods, including deconstruction and material recovery, often involve higher labor and processing costs compared to conventional demolition and landfill disposal. Furthermore, storage and transportation costs can make secondary materials more expensive than newly manufactured alternatives, particularly if the materials need to be processed or tested before reuse (Nieuwhoff, 2022; Shan, 2023). The lack of financial incentives, such as subsidies or tax reductions, further discourages material reuse, as existing tax structures tend to favor newly produced materials over reused alternatives (Fufa et al., 2023; Holly et al., 2023).

Regulatory and Standardization

Current procurement frameworks and construction standards are not always aligned with circular economy principles. Many regulations, including building codes and procurement policies, prioritize new materials that meet established quality and safety criteria over reused components, which may lack standardized certifications (Van der Mark, 2024). In addition, waste management regulations can complicate reuse pathways, as some recovered materials may still be classified as waste rather than usable resources, creating legal and administrative hurdles for their reintegration into construction projects (Van Uden et al., 2025).

Logistical and Coordination

The lack of coordination between stakeholders in the material cycle further limits the effectiveness of secondary material circulation. Contractors, material suppliers, designers, and policymakers often operate in silos, resulting in inefficiencies in matching supply with demand (Köhrer, 2024). Additionally, poorly organized material collection and redistribution networks contribute to unnecessary transit movements and logistical bottlenecks, increasing costs and environmental impacts (Shan, 2023). The time mismatch between demolition and new construction projects also presents a challenge, as recovered materials are often not available precisely when they are needed, leading to lost reuse opportunities (Van Uden et al., 2025).

These barriers highlight the need for spatial and logistical infrastructures capable of systematically managing secondary material flows. Circular Construction Hub (CCH) has emerged in both literature and practice as promising solutions to these challenges, offering centralized facilities for the collection, sorting, quality control, and redistribution of secondary construction materials. As such, CCH is not just a novel concept but a strategic response to the systemic inefficiencies hindering circularity in road infrastructure and construction more broadly.

2.4. Circular Construction Hub (CCH)

In response to the logistical, economic, and coordination barriers that hinder high-value material reuse, the concept of the Circular Construction Hub (CCH) has emerged in academic literature and industry practice as a strategic infrastructural solution. By providing centralized facilities for collection, sorting, and redistribution, CCHs professionalize the management of secondary material flows. This section examines the CCH concept, tracing its evolution and typologies, defining its core functions and strategic role, and discussing the logistical infrastructure required for integration. It also grounds the challenge of siting these facilities in facility-location theory and synthesizes a list of site selection criteria from existing research.

2.4.1. Concept and Evolution

Circular Construction Hub (CCH) has evolved from earlier models of construction hubs, which prioritized logistical efficiency without explicitly addressing circular economy principles. Traditional hubs initially focused on logistics coordination, traffic management, material storage, and product distribution, aiming primarily to reduce transportation costs, loads, and emissions. However, these early hubs typically

typically lacked systematic mechanisms to promote the reuse and recycling of secondary construction materials (Shan, 2023).

In response, dedicated storage hubs emerged to address temporal mismatches, storing secondary materials from demolition until their subsequent reuse in new projects. Building on these preliminary steps, CCH presents an integration of logistics and circular economy strategies. Unlike earlier iterations, CCHs explicitly facilitate secondary material collection, processing, storage, and redistribution, thus supporting sustainable material flows by ensuring that construction and demolition waste can be effectively reintroduced into new building cycles (Tsui et al., 2023; Yang et al., 2023). As shown in Figure 2.6, Metabolic (2022) visually illustrates the evolution of construction hubs, distinguishing traditional logistical hubs that primarily coordinate transport and storage, storage hubs specifically for temporarily housing secondary materials, and circular construction hubs explicitly designed as collection and trading points to enable material reuse and circulation.

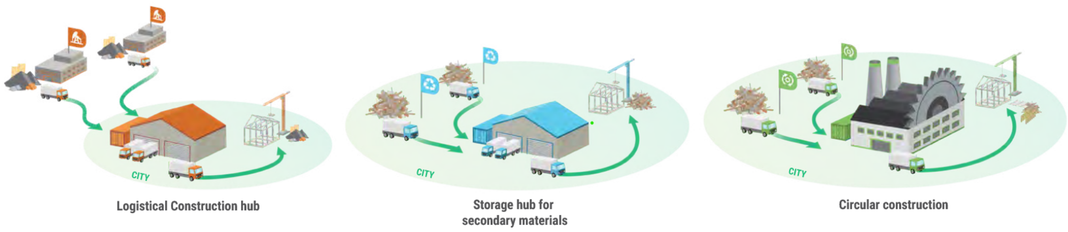


Figure 2.6: Three types of construction hubs (Metabolic, 2022).

Multiple definitions and terminologies for construction hubs exist in the literature, yet there is no single, universally accepted term that describes locations dedicated to collecting secondary materials and reducing dependence on virgin resources. Although some authors refer to these facilities as circular building material hubs, others adopt different labels for essentially similar operational models. Nieuwhoff (2022) categorized a total 12 distinct types of construction hubs, which could be seen in Table 2.1

Table 2.1: Category of construction hubs (Nieuwhoff, 2022).

Function	Terminology	Explanation
Not Circular	Construction site hub	For temporary, project-specific storage
	Suppliers' building material hub	Primarily logistical without circular purposes
	Floating building material hub	Specialized logistical facility utilizing waterways
Circular	Circular craft center	Serves as a marketplace and repository for smaller-scale secondary materials
	Circular building material hub	Provides storage and marketplace services specifically for secondary materials
	Circular multimodal building material hub	Storage and redistribution of secondary materials across multiple transport modes
	Circular raw building material hub	Manages bulk materials with logistics and secondary storage
Others	Multimodal material hub	Facilitates construction logistics through various transport modalities
	Mandatory building material hub	Coordinates logistics across multiple projects within urban areas
	Building material hub with urban development	Coordinates material flows for urban development projects
	Raw building material hub	Manages logistics of bulk materials
	Prefabrication building material hub	Specializes in logistics for prefabricated modular construction elements

Nieuwhoff categorized the hubs based their function (circular, non-circular, and others). The generalized term Circular Building Material Hub (CBMH) is used to represent the a location where secondary materials are collected and reused, as there is no universally agreed-upon definition.

Tsui et al. (2023) identified typology based on hub's scale and perspectives. The categorization of these hub types was based on two key dimensions: the geographic extent of their operations (a broader or a localized area) and their primary function (processing or redistribution of recovered materials).

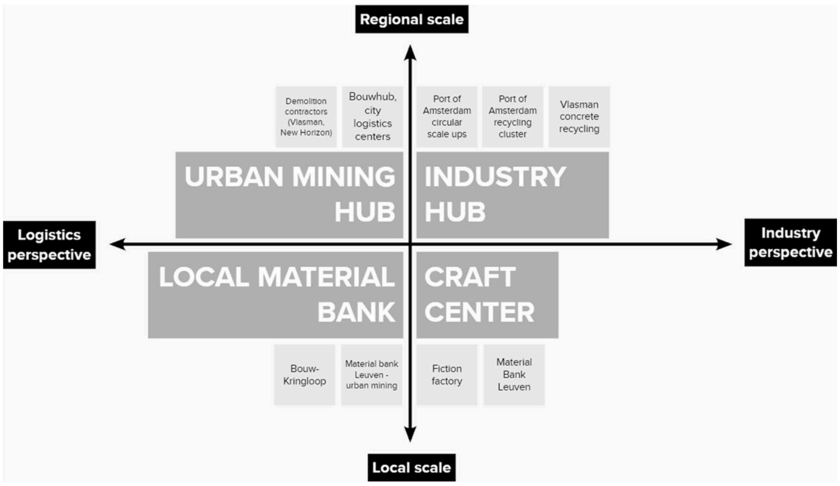


Figure 2.7: Four types of circular construction hubs (Tsui et al., 2023).

The interviews and document reviews done resulted in four types of hub: industry hubs, urban mining hubs, craft centers, and local material banks (Figure 2.7). Industry hubs are for large-scale and industrial circular activity, urban mining hubs are for sorting, storing, and distributing building components, craft centers use construction waste to make furniture, and local material banks collect, store, and re-sell residue flows ignored by larger companies, and are usually co-located with craft centers.

Expanding on Nieuwhoff's classification, Van der Mark (2024) categorized these terminologies by circularity level and operating scale, using a similar approach to Tsui et al.'s four-axis hub categorization, as shown in Figure 2.8.

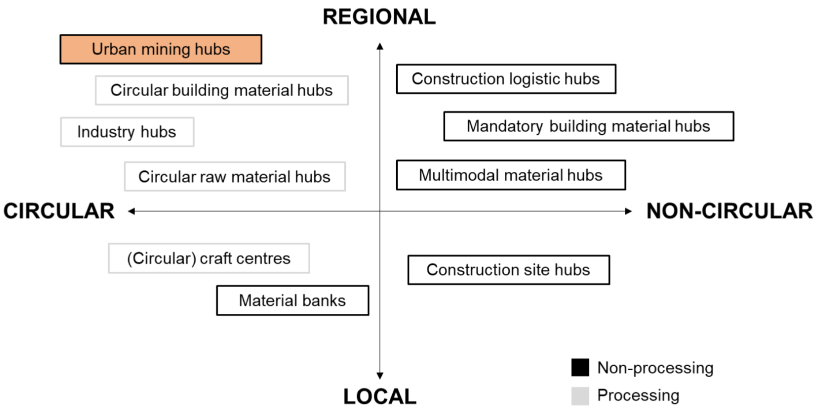


Figure 2.8: Division of hubs by Van der Mark (2024).

On the circularity axis, hubs are classified based on their material management practices and their contribution to circular economy goals. Circular hubs primarily handle secondary materials reclaimed from existing built environment stocks. In contrast, non-circular hubs focus predominantly on logistical operations, managing the flow of primary (virgin) materials to construction projects without a direct emphasis on reuse or recycling. The second axis, operating scale, distinguishes hubs by their geographical coverage. Regional hubs serve larger geographic areas, potentially encompassing multiple municipalities or regions, facilitating a wider aggregation and distribution of materials. Local hubs, conversely, cater to smaller, more concentrated areas such as individual cities or specific neighborhoods.

Despite variations in terminology, the essential role of these hub, which is facilitating efficient secondary material flows and reuse, is consistently emphasized across related studies.

2.4.2. Core Functions and Strategic Role

One of the primary roles of a CCH is to bridge the temporal gap between the availability of reclaimed materials and their demand in new construction projects. Conventionally, usable components from demolished structures often become waste if there is no immediate reuse option available nearby. CCH mitigate this by matching available materials to potential future projects, effectively serving as brokers that link supply with demand. For example, if an old building is deconstructed in January, yielding numerous reusable materials, but the construction of a new building that could utilize these materials is scheduled for August, the hub can warehouse these materials. Such a buffering function ensures that valuable components are preserved and not prematurely discarded. A practical illustration of this function is provided by the city of Houston in the United States, where over one-third of the local waste stream comprises construction materials. The city's Reuse Warehouse intervenes by accepting and temporarily storing surplus materials, such as lumber and fixtures, until non-profit organizations or schools can utilize them (City of Houston, 2015). This temporal bridging significantly reduces waste and creates a reservoir of supplies available for future reuse.

In addition to addressing timing mismatches, CCH functions effectively as logistical coordinators, mitigating spatial and material condition mismatches. When reclaimed materials are sourced far from potential reuse locations or require preliminary processing, hubs centralize these tasks. For example, Material Cultures and Arup (2022) propose a Circular Economy Construction Hub (CECH) in Newham, London. Their identified precedent, Rotor DC in Brussels, highlights practical refurbishment processes, such as removing mortar from ceramic tiles and cleaning sanitary equipment. Such activities illustrate the essential role of hubs in preparing salvaged materials for direct reuse at construction sites, especially beneficial when receiving sites lack adequate processing facilities. The centralization logistical nature of hub implicitly supports optimized transportation efficiency by reducing the frequency and distance of transportation movements, which lead to lowering emissions associated with sourcing from multiple dispersed locations.

Beyond physical logistics, CCH increasingly relies on digital tools to facilitate efficient reuse. Köhrer (2024) emphasizes that hubs can significantly support reuse by providing detailed digital information about materials, utilizing online marketplaces, and maintaining accurate online inventories. Modern hubs avoid manual logs and ad-hoc spreadsheets by implementing sophisticated digital systems such as mobile apps, QR codes, or Building Information Modeling (BIM) integrations to create structured and easily accessible inventories. These digital platforms enable multiple stakeholders, including project managers, hub operators, and potential buyers, to access real-time data on available materials simultaneously. Vrijders et al. (2022) highlight the advantages of digital inventory tools, including speed in data collection and reporting, ease of incorporating images and standardized descriptions, and collaborative access from multiple locations, thus significantly enhancing material tracking and management capabilities.

However, digital inventories alone are insufficient to ensure material reuse; CCH also requires robust mechanisms to actively match materials to specific projects and facilitate transactions. This introduces another critical function: the marketplace and brokerage role. CCH often operates as marketplaces, either physical, digital, or hybrid, where buyers and sellers can efficiently meet and exchange materials. Additionally, hubs can adopt an active brokerage function, proactively connecting available supplies with identified demands. For instance, project managers can search a digital marketplace for specific items such as ”reclaimed oak flooring” or ”second-hand light fixtures” and receive detailed lists including quantities, conditions, and origins. Moreover, marketplaces enable stakeholders to proactively post material requests, allowing hubs to reserve matching salvaged items from future demolitions. According to the CityLoops urban circularity program (2021), digital marketplaces are essential for effectively tracking, mapping, and matching resources. They enhance transparency by clearly indicating the availability, quality, location, and cost of materials. Thus, centralized marketplaces amplify the visibility of secondary materials, promoting their wider adoption across the construction community.

In a broader sense, the integration of core CCH functions such as addressing temporal and logistical mismatches, maintaining digital inventories, and facilitating marketplace transactions into the strategic framework of the Construction Logistics Control Tower (CLCT) can significantly enhance circularity and logistics efficiency in the construction sector. Harmelink (2025) illustrate how CLCT centrally coordinates logistics, facilitate data exchange, and optimize transport across multiple construction projects, effectively reducing emissions and logistical inefficiencies.

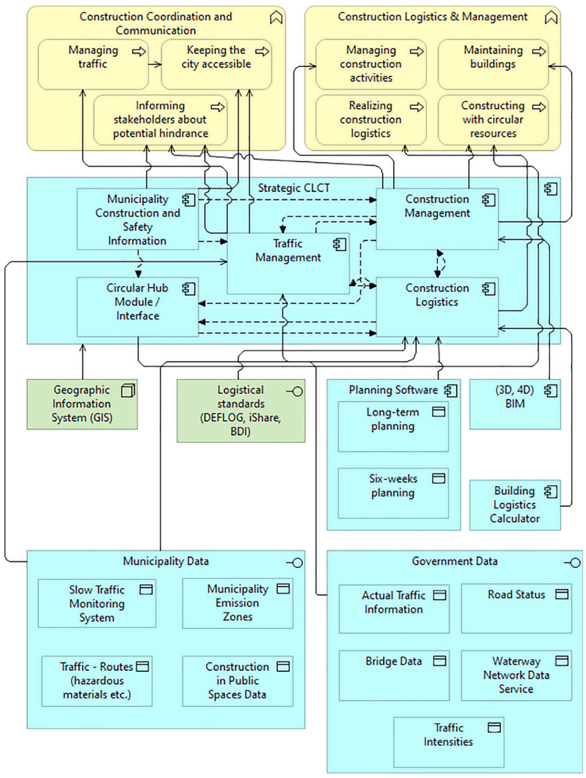


Figure 2.9: Strategic CLCT and its technologies (Harmelink et al., 2025).

The integration of CCH functions into the CLCT framework is visually represented by Vrijhoef and Harmelink (2024) in Figure 2.9. This diagram illustrates key interactions between various stakeholders, strategic modules, and data sources within the CLCT concept. The CCH, represented by Circular Hub Module, connects the hub's logistical and brokerage roles directly with municipal construction and safety information, governmental data (such as traffic intensity and emission zones), planning software including BIM, and strategic traffic management functions. By embedding the practical operations of CCH into the CLCT's strategic approach, such as bundling material transport, facilitating inter-project material reuse, and optimizing overall logistics planning, both micro-level material management and macro-level urban logistics efficiency can be enhanced.

2.4.3. Logistical Infrastructure and Integration

CCH ultimately depends on robust physical infrastructure to function effectively, despite often conceptualized through digital inventories, strategic coordination, and policy frameworks. As CCH transition from concept to implementation, spatial logistics have emerged as a critical constraint, especially in dense urban environments. Cities in the Netherlands are increasingly turning to intermediary logistical models, to bridge the gap between circular ambitions and on-the-ground material management.

At the municipal level, cities such as Amsterdam and Utrecht have implemented construction consolidation centers, or *bouwhubs*, to serve as logistical intermediaries for both construction and other industries. Instead of allowing uncontrolled, piecemeal deliveries to inner-city work sites, materials are first transported in bulk to these hubs and then repackaged for just-in-time delivery to the city center. In Amsterdam, the municipality has established several *bouwhubs* as pilot projects, one of them is Amsterdam Logistics City Hub (Figure 2.10). Similarly, in Utrecht, a pilot renovation project utilizing a *bouwhub* led to a 69% reduction in delivery trips, along with a 68% reduction in emissions and a 39% increase in productivity (van Luik et al., 2023). These outcomes demonstrate how *bouwhubs* not only streamline material deliveries but also contribute to broader urban benefits, including reduced parking pressure around construction sites, fewer costly errors, and more efficient supply chain coordination.

Figure 2.10: Amsterdam Logistics City Hub at Ankerweg (Metabolic, 2022).

While *bouwhubs* have demonstrated substantial benefits in streamlining urban construction logistics, it is important to note that their role is not inherently circular (see subsection 2.4.1). As stated previously, a clear distinction must be made between logistical construction hubs, which primarily handle the distribution of new materials to construction sites, and CCH, which are designed to process, store, and redistribute secondary materials for reuse. In this typology, *bouwhubs* are best understood as logistical intermediaries that may support circularity but do not guarantee it. Their circular potential depends on whether they are integrated into reuse pathways, handle reclaimed materials, and are linked with digital inventory systems or material marketplaces. Without such features, a *bouwhub* remains a valuable logistics solution, albeit not a circular one.

Nevertheless, the challenge of securing suitable storage and processing locations is not unique to CCH. Whether serving conventional construction logistics or aiming to support circular material flows, all hub models operating in urban areas face similar spatial and regulatory constraints. As noted from Larsson and Gammelsæter (2023), space for stockpiling soil, gravel, or demolition waste is scarce, and land-use regulations can pose conflicts. As a result, whether the hub is intended to distribute new materials or process recovered ones, logistical efficiency and material circularity alike are compromised when materials must be hauled to distant storage or disposal sites. The report further highlights the importance of early planning to allocate space for temporary storage and processing near project sites, allowing materials to be sorted, treated, and reused rather than prematurely discarded. This insight aligns with the study by Tsui et al. (2024), which emphasizes an urban circular hub often requires 1–2 hectares of space, good accessibility, and integration into multimodal transport networks. Without such forward-looking planning, the logistical and environmental benefits of material reuse will remain largely theoretical.

2.4.4. Facility-Location Theory

The strategic challenge of determining optimal locations for Circular Construction Hubs (CCHs) and configuring the associated logistics network falls squarely within the well-established academic domain of facility-location theory and network-design theory. These fields, rooted in operations research and geography, provide a rich set of concepts, models, and solution approaches for siting facilities and structuring flows to meet specific objectives, typically related to cost efficiency, service coverage, or system resilience.

A fundamental aspect of this domain is the Facility-Location Problem (FLP), which generally seeks to identify the best sites for one or more facilities from a set of potential candidates to serve a distributed set of demand points (Rodrigue, 2024). Common objectives in FLPs include minimizing total weighted travel distance or cost, as exemplified by p-median models (Hakimi, 1964), which directly align with the goal of minimizing tonne-kilometers (t-km) in freight transport. Another class of models, coverage models (e.g., Set Covering or Maximal Covering Location Problems), prioritizes ensuring that demand points are within a specified service distance or time from a facility, a crucial consideration for ensuring accessibility to CCHs from dispersed material arising ”hot-spots” (Church & Velle, 1974).

When material flows benefit from consolidation before reaching final destinations or processing points, Hub-and-Spoke (H&S) network design principles become highly relevant. Hub location models, such as the p-hub median problem, aim to optimize the placement of central hubs to leverage economies of scale on inter-hub links, even if it introduces multi-stage journeys (Campbell, 1994; O'Kelly, 1986). However, in dense urban contexts or with specific freight characteristics, the practical limits of consolidation and potential diseconomies from either having too many hubs (leading to redundancy and high storage costs) or potentially overly large ones (impacting transportation efficiency) (Tsui et al., 2024).

Solving these complex location and network design problems, which are often NP-hard for realistic scales, typically necessitates the use of heuristic solution approaches. Although exact optimization methods can guarantee optimality for smaller instances, heuristics provide effective and computationally feasible ways to find high-quality, near-optimal solutions for larger, real-world problems (Hinkamp & Ismael, 2023). Common types include constructive heuristics, such as greedy algorithms which make locally optimal choices at each step Gwalani et al. (2021) and Tadić et al. (2023), and iterative improvement heuristics (local search), which refine an initial solution by exploring its neighborhood, for instance, through location-allocation swaps (Schmidt, 2023).

Collectively, these established principles and models from facility-location and network-design theory provide the essential theoretical background for this thesis. The concepts of p-median optimization directly inform the objective of tonne-kilometer minimization pursued in the evaluation of the Decentralized network. Coverage model principles implicitly guide the initial GIS-based suitability analysis by defining service reach and feasible areas for CCH and TSS siting. The theory of Hub-and-Spoke networks, including considerations of consolidation benefits and potential urban saturation effects, provides the framework for designing and evaluating the connection between hub and its spokes.

2.4.5. Site Selection Criteria

The strategic siting of Circular Construction Hubs (CCHs) is a complex decision-making process, demanding consideration of diverse factors to ensure operational success and alignment with sustainability objectives, as suggested by previous subsection. A review of academic literature on siting analogous facilities, such as logistics hubs, waste management sites, and industrial parks reveals a common suite of criteria. Although specific quantitative thresholds and their relative importance are highly context-dependent, a consistent set of considerations emerges.

These criteria, drawn from numerous studies, can be broadly categorized into environmental, socio-economic, infrastructure, and regulatory factors. Table 2.2 synthesizes key criteria identified in the literature.

Table 2.2: Site selection criteria for CCH from several literature.

Category	Criterion	Details	References
Environmental	Water resource protection	Minimum buffer distance from surface water bodies and potentially sensitive groundwater areas	Akther et al. (2019), Cobos-Mora et al. (2023), Demesouka et al. (2016), Ding et al. (2018), Donevska et al. (2021), Loureiro et al. (2023), Nuhu et al. (2022), and Özkan et al. (2019)
	Natural areas protection	Minimum buffer distance from legally protected natural/ecological zones	Akther et al. (2019), Cobos-Mora et al. (2023), Demesouka et al. (2016), Ding et al. (2018), Donevska et al. (2021), Loureiro et al. (2023), and Shahparvari et al. (2020)
Socio-economic	Distance from residential areas	Minimum buffer distance from residential zones to mitigate noise, dust, and traffic impacts	Akther et al. (2019), Alqahtani et al. (2024), Cobos-Mora et al. (2023), Demesouka et al. (2016), Ding et al. (2018), Donevska et al. (2021), Loureiro et al. (2023), Özkan et al. (2019), and Shahparvari et al. (2020)

Continued on next page

Table 2.2 continued from previous page

Category	Criterion	Details	References
	Sensitive facility buffer	Minimum buffer distance from schools, hospitals, and potentially major tourist/recreation areas	Akther et al. (2019), Cobos-Mora et al. (2023), Ding et al. (2018), Donevska et al. (2021), Loureiro et al. (2023), and Shahparvari et al. (2020)
Infrastructure	Road network accessibility	Proximity and access quality to the major road network suitable for truck transport	Acar et al. (2015), Akther et al. (2019), Alqahtani et al. (2024), Cobos-Mora et al. (2023), Demesouka et al. (2016), Ding et al. (2018), Donevska et al. (2021), Loureiro et al. (2023), Nuhu et al. (2022), Önden et al. (2016), Özkan et al. (2019), and Shahparvari et al. (2020)
	Proximity to multimodal transport (rail/waterways)	Proximity to rail or waterway infrastructure	Acar et al. (2015), Nuhu et al. (2022), Önden et al. (2016), and Shahparvari et al. (2020)
	Proximity to material supply	Proximity to anticipated areas of high road maintenance activity	Ding et al. (2018), Donevska et al. (2021), and Tsui et al. (2023)
	Suitable land size	Availability of sufficient land area (e.g., >= 1 ha) for hub operations and storage	Tsui et al. (2023)
Regulatory	Compatible land use zoning	Location within land use zones designated as suitable for industrial/logistical activities	Akther et al. (2019), Alqahtani et al. (2024), Cobos-Mora et al. (2023), Demesouka et al. (2016), Ding et al. (2018), Donevska et al. (2021), Loureiro et al. (2023), Nuhu et al. (2022), Özkan et al. (2019), and Shahparvari et al. (2020)
	Restricted area avoidance	Exclusion from legally restricted zones (e.g., military, specific safety zones).	Akther et al. (2019), Alqahtani et al. (2024), Ding et al. (2018), and Nuhu et al. (2022)

Table 2.2 presents several important themes that are essential for selecting suitable sites for CCH facilities. Environmental protection is a top priority. This includes maintaining minimum buffer distances, often several hundred meters, from surface water, sensitive groundwater areas, and protected natural zones to prevent ecological harm (Akther et al., 2019; Alqahtani et al., 2024; Ding et al., 2018).

Socio-economic factors focus on minimizing negative impacts on local communities. This involves placing sites at a safe distance from residential areas to reduce disturbances such as noise and traffic. Similar buffers are recommended for sensitive locations such as schools and hospitals (Akther et al., 2019; Alqahtani et al., 2024; Ding et al., 2018).

Operational feasibility depends on the availability of adequate infrastructure. Important aspects include good road access for trucks, proximity to sources of material supply or waste generation, and sufficient land area. For example, a minimum of one hectare is suggested by Tsui et al. (2023). For larger hubs, having access to multiple transport modes can also be beneficial (Acar et al., 2015; Nuhu et al., 2022).

Regulatory compliance is also crucial. Sites must be located in areas where land use zoning allows for industrial or logistical activities. In addition, they must avoid locations that are legally restricted from development (Akther et al., 2019; Cobos-Mora et al., 2023).

Although Table 2.2 provides a structured summary of these key themes, the broader literature offers more detailed criteria. These include geophysical conditions such as slope and soil type, economic factors like land and transport costs, and a wider range of environmental considerations. Often, these criteria come with specific quantitative recommendations (see Donevska et al. (2021) and Özkan et al. (2019).

Overall, while there is a general framework for site selection, its practical application must be adapted to the specific local context. Factors such as data availability, policy conditions, and the operational model of the CCH must be taken into account. This understanding directly informs the methodology used in Chapter 3 for identifying potential CCH sites in Amsterdam.

2.5. Temporary Storage Site (TSS)

The transition toward circular economy practices in the construction sector, particularly in urban environments, demands adaptive, efficient, and sustainable logistics solutions. Temporary Storage Sites (TSSs) represent one such solution; they are smaller, tactical facilities designed for short-term buffering and local consolidation. In academic literature, this concept is most closely aligned with the emerging typology of the micro-hubs. Micro-hubs have emerged as a critical typology with direct relevance to project-scale material handling, just-in-time delivery coordination, and transshipment logistics for secondary construction materials.

Originally developed to optimize last-mile logistics in parcel distribution, micro-hubs are increasingly recognized for their potential in supporting circular construction operations, particularly in dense city centers where vehicle restrictions, space limitations, and sustainability mandates converge.

2.5.1. Core Characteristics

Micro-hubs are defined by the Urban Freight Lab (2020) as *"Logistics facilities inside the urban area boundaries where goods are bundled ... and allow a mode shift to low (or zero) emission vehicles or soft transportation modes (e.g., walking) for last yard deliveries"*. These facilities enable a two-stage delivery model: (1) consolidated transport from outer depots to the micro-hub, and (2) last-yard distribution to end-users using green transport modes such as cargo bikes or autonomous delivery robots (Anderluh et al., 2020; De Bok et al., 2024).

Recent analysis from the OECD (2024) highlights that such hubs do not need to be permanent fixtures. There is a growing recognition of the value of temporary micro-hubs that could be quickly deployed, moved, and re-converted to support the dynamic nature of urban logistics demand. This emerging typology leverages underutilized urban spaces, such as vacant parking lots or daytime-empty bus depots, for logistics activities like transshipment to more sustainable last-mile vehicles.

Micro-hubs are a scaled-down variant of CCH, offering closer proximity to end-users and targeting short-range logistics within dense urban cores (Janjevic & Ndiaye, 2014; Verlinde et al., 2012). In construction, this typology aligns with what are often referred to as temporary material staging ares or mobile consolidation depots, adapted to project-based operations.

2.5.2. Logistical Relevance

The utility of micro-hubs lies in their ability to decompress urban freight flows and create cleaner, more predictable logistics operations within constrained city environments. The simulation study of micro-hub evaluation in City of Rotterdam by De Bok et al. (2024) finds that: (1) micro-hubs reduce total vehicle kilometers, especially when last-mil tasks are pooled across operators, (2) smaller, zero-emission vehicles are operationally feasible for high-density delivery zones, and (3) spatial optimization and consolidation density are key. Moreover, the simulation revealed that the simulation revealed that location and demand density, not just number of hubs, determine effectiveness of these facilities, which aligns with findings by Buldeo Rai et al. (2022) study.

This concept is already being successfully implemented through innovative public-private collaborations. In Paris, for example, flexible use of urban space for logistics is evident in two notable cases (OECD, 2024):

- Amazon's partnership with RATP: Repurposing public bus depots during off-peak hours as micro-hubs for cargo bike deliveries.
- Sogaris's transformation of an underutilized area: Converting space beneath a ring road into a logistics facility on a 12-year public domain lease. The entire structure is designed to be dismantled and recycled if the city chooses not to renew the lease.

2.5.3. Definition for This Study

For the purposes of this thesis, these concepts are operationalized as the Temporary Storage Site (TSS). Drawing on the academic definition of a micro-hub and the practical examples of temporary, repurposed logistics spaces, a TSS is defined as a small-scale, potentially non-permanent site used for the consolidation and/or local distribution of circular construction materials. In the context of this study's reverse logistics model, a TSS serves several key functions:

- Interim storage points for reclaimed materials awaiting redistribution.
- Buffer zones for staging materials from demolition/deconstruction.
- Multi-project logistic nodes serving clustered sites (e.g., multiple maintenance projects within a district).
- Transshipment points for transporting reclaimed materials using smaller, more environmentally friendly vehicles to off-site processing hubs.

2.6. Case Study: Amsterdam

To ground the theoretical frameworks of circular logistics and CCH networks in real-world context, this thesis uses Amsterdam as its case study. Amsterdam offers an ideal setting for analysis because of its ambitious circularity policies, detailed maintenance data, dense urban structure that creates logistical challenges, and a history of material standardization that supports reuse. This section provides context for the case study, outlining Amsterdam's circularity policies, the 'Puccini Method' for material standardization, and an analysis of upcoming road maintenance projects, which supply the foundational data on material flows for the modeling in this thesis.

2.6.1. General Information

Amsterdam has positioned itself as a frontrunner in the transition toward a circular economy, setting ambitious targets to become a fully circular city by 2050. As part of this long-term vision, the municipality has committed to halving the use of new raw materials by 2030. The built environment, encompassing both buildings and infrastructure, has been identified as one of three key value chains central to achieving this transition, due to its substantial environmental impact and the city's regulatory leverage in shaping construction and maintenance practices (City of Amsterdam, 2020).

In its 2020–2025 circular strategy, Amsterdam outlined a comprehensive agenda for the built environment. Circular construction is defined in terms of minimizing environmental harm while also emphasizing material efficiency, reuse, modular design, and adaptability. All new urban developments and public space designs are required to integrate circular criteria, with a goal for 50% of renovations and maintenance activities to adhere to circular principles by 2025 (City of Amsterdam, 2020). These commitments are reaffirmed and operationalized in the 2023–2026 Implementation Agenda, which introduces targeted actions such as promoting bio-based insulation, prioritizing reused materials through the 'reuse, unless' principle, and using material passports and Environmental Performance (MPG) scoring in tenders for public buildings and infrastructure (City of Amsterdam, 2023).

To support transition to circular economy, Amsterdam employs a broad array of policy instruments that can be grouped into three categories: regulatory, economic, and soft instruments. Regulatory instruments include environmental permitting, construction standards, and land-use regulations that incorporate circular principles into planning and development processes. Economic tools focus on fiscal incentives and circular procurement, such as adjusting land prices or applying lifecycle-based cost assessments to make reused materials financially attractive. The city also leads by example through its own procurement policies, including circular tenders for public assets like school buildings and sports grounds. Soft instruments reinforce these efforts through knowledge sharing, research collaboration, digital tool development (e.g., material passports), and engagement with public-private partnerships. The city also promotes citizen involvement and awareness campaigns to cultivate public support for circular goals.

Altogether, this multi-layered policy framework establishes a strong institutional foundation for circular construction in Amsterdam. It not only signals political commitment, but also creates practical conditions for scaling up reuse practices across the built environment. For infrastructure and road maintenance in particular, these policies open a pathway toward more structured and coordinated material flows, an area where CCH could serve as key logistical and operational nodes.

2.6.2. Puccini Method

One of the most distinctive aspects of Amsterdam's urban design strategy is the Puccini Method, a standardized framework developed by the municipality to guide the construction and maintenance of public spaces, including roads and pavements (Gemeente Amsterdam, 2024). Formalized in the latest edition of the *Handboek Rood*, the method outlines technical profiles, material specifications, and visual guidelines to ensure a coherent, durable, and climate-resilient urban environment. It regulates the use of paving materials, construction details, and spatial layouts across different urban zones, supporting both functional consistency and aesthetic unity throughout the city.

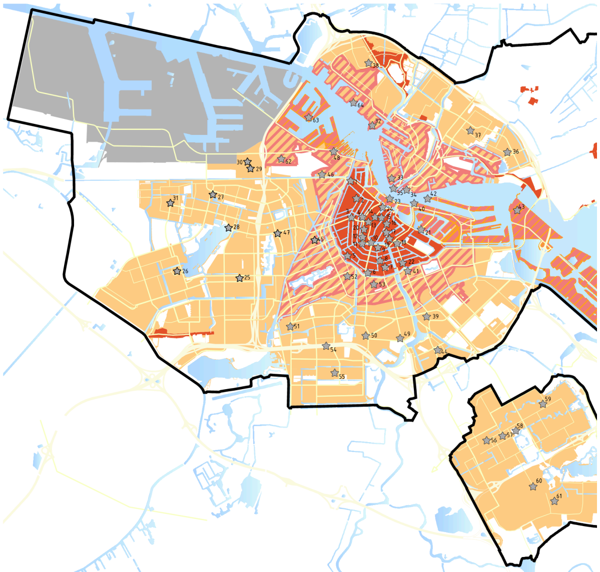


Figure 2.11: Color-coded zoning standards within Amsterdam (Gemeente Amsterdam, 2024).

Figure 2.11 shows how the Puccini Method distinguishes different zones within the city according to the standards applied in each. At the core of the Puccini Method is a commitment to material standardization. The *Vloerkaart Puccinimethode Rood*, a city-wide map embedded within the framework, prescribes a limited palette of approved materials for specific urban zones.

Across much of the city, pavements and sidewalks rely on small element paving, particularly 30x30 *betontegels* (concrete tiles) and *gebakken klinkers* (baked clay bricks), either in standard or larger sizes. The use of standardized materials supports 'narrowing' strategies by simplifying sorting, and aligns with 'slowing' loops through design-for-maintenance principles (see Section 2.2).

2.6.3. Road Maintenance in Amsterdam

Amsterdam's urban road infrastructure, with its extensive SRN, relies heavily on pavement types that lend themselves well to circular practices, particularly in the maintenance context. Beyond conventional asphalt and stone mastic surfaces, the city makes extensive use of concrete bricks, paving stones, clay bricks, and kerbstones, collectively referred to as *elementverharding* or elemental paving (Fröhling, 2023). These small, modular components are not only durable and aesthetically aligned with the city's historic character, but also suitable for disassembly and selective reuse. The Puccini Method reinforces this approach by prescribing standard material profiles such as 30x30 concrete tiles and baked bricks across the city's five zoning categories (Gemeente Amsterdam, 2024).

The scale, nature, and timing of upcoming road maintenance activities in Amsterdam underscore the significant potential for recovering these materials and the necessity for strategic logistical planning. Analysis of municipally planned projects for the period 2025-2030 reveals that major maintenance (GO or *groot onderhoud*) and replacement (VV or *vervangings*) activities will dominate the workload, accounting for approximately 49.0% and 36.7% respectively of the total project area scheduled for intervention (the pie chart in Figure 2.12). These project types commonly involve the extensive removal and potential replacement of existing paving elements, thus ensuring a substantial and continuous stream of materials suitable for circular management. The temporal distribution of this work, as illustrated in the bar chart of Figure 2.12 indicates a significant surge in activity beginning in 2025, peaking between 2026 and 2028 when over 1 million m² of surface area is projected for intervention annually. Importantly, this chart also highlights that key reusable materials such as concrete tiles (*betontegel*), concrete paving stones (*betonsteen*), and bricks (*gebakken steen*) consistently represent a significant portion of the works planned each year, ensuring a steady potential supply for the CCH network.

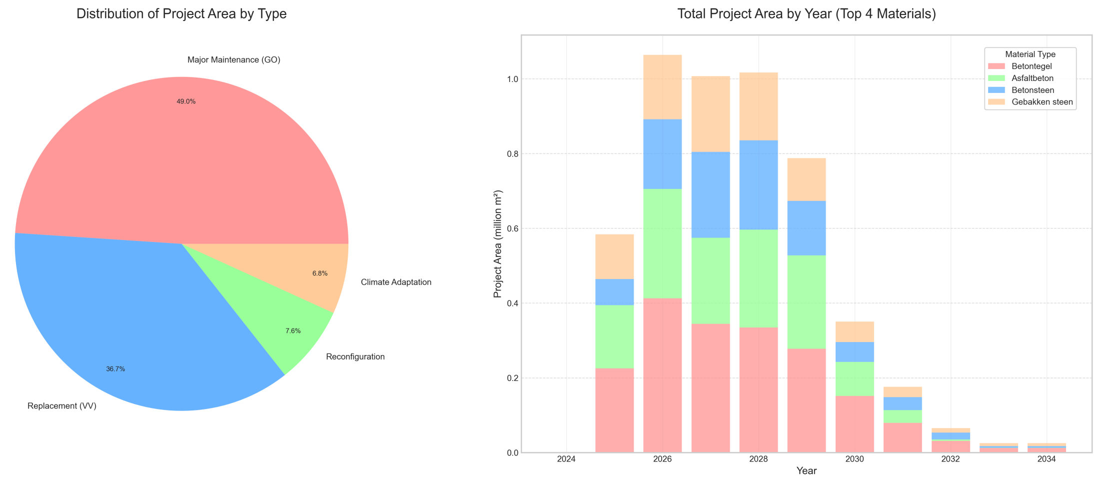
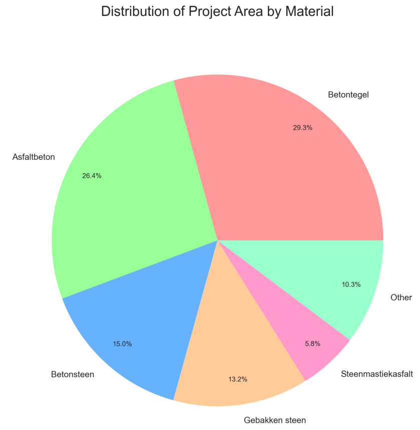


Figure 2.12: Project area analysis showing distribution by project type (left) and total area by year (right).

The material composition of these planned projects further confirms the relevance of focusing on elemental paving. As shown in the pie chart of Figure 2.13, *betontegel* constitute the largest single material category by surface area, accounting for 29.3% of the total. *betonsteen* (15.0%) and *gebakken steen* (13.2%) also represent substantial portions. *Asfaltbeton* (26.4%) covers a significant area, the combined share of the target reusable paving elements is predominant, indicating a vast potential for high-value recovery through a dedicated CCH system. The spatial distribution of these maintenance activities, detailed in the bar chart of Figure 2.13, is widespread across all city districts yet exhibits notable concentrations. Amsterdam Noord is projected to have the largest surface area undergoing road maintenance (approximately 0.86 million m^2), with Oost (approx. 0.54 million m^2) and Zuid (approx. 0.51 million m^2) also facing substantial workloads. This geographically dispersed yet somewhat clustered pattern of materials across Amsterdam's dense urban form presents distinct logistical challenges for efficient collection and transport, thereby emphasizing the potential benefits of strategically located CCHs and Temporary Storage Sites (TSS).



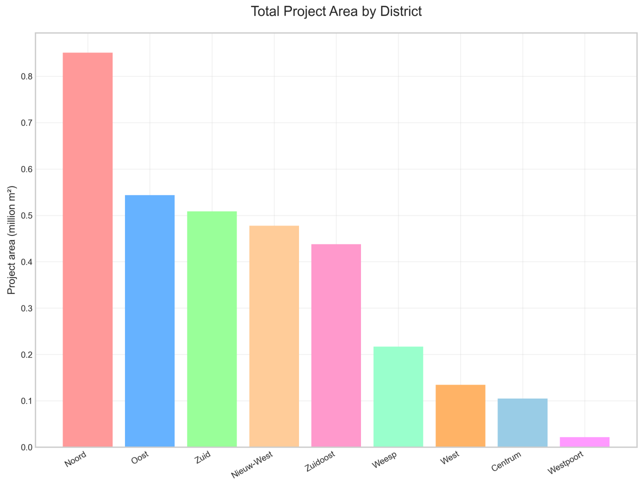


Figure 2.13: Project area analysis detailing distribution by material type (left) and total area by district (right).

Current logistical practices for road maintenance in Amsterdam already acknowledge some of these challenges. The Puccini Method itself promotes minimal intervention and the relaying of existing paving elements where feasible. For more extensive works, the municipality and its contractors often utilize off-site storage solutions, partly due to the city's compact nature which intensifies the economic and environmental costs of inefficient transport and on-site material staging. Furthermore, the *Algemene Plaatselijke Verordening* (APV) imposes restrictions on placing construction materials on public roads without a permit, often leading to requirements for timed deliveries and the use of external depots or emerging construction logistics hubs (*bouwhubs*) (Gemeente Amsterdam, 2008). Although these existing hubs primarily focus on streamlining the delivery of new materials (Metabolic, 2022), they demonstrate an acceptance of consolidated logistics. This existing framework, combined with the clear, data-driven picture of upcoming material flows, suggests a strong case for developing dedicated CCHs tailored to the specific needs of secondary road maintenance materials. Amsterdam serves as an excellent and compelling case study for developing and assessing a structured approach to siting CCH and designing their network. This is due to a combination of factors: the city's proactive policies on circularity, substantial and well-documented streams of reusable standardized materials from extensive planned maintenance, pressing logistical difficulties in a densely populated urban area, and the wide availability of data.

Despite these advances, significant logistical and spatial challenges remain. As noted by Larsson and Gammelsæter (2023), suitable areas for temporary storage of reclaimed materials are scarce within city limits, and zoning conflicts often impede their use. Both their work and Tsui et al. (2024) emphasize the need for early planning and space allocation to support circular practices. Without such infrastructure, reclaimed materials are often transported to distant facilities, undermining their reuse potential and increasing environmental impact.

Together, these practices and constraints illustrate the complex interplay between material typologies, maintenance strategies, and logistical systems in Amsterdam's pursuit of circular road infrastructure. Even though the city has established a promising foundation, fully realizing circular ambitions in road maintenance will require deeper integration between reuse objectives and on-the-ground logistical planning.

3 Methodology

3.1. Overview

This chapter details the systematic research methodology employed to address the overarching research question: "How can Circular Construction Hubs be strategically located and configured to support material reuse in urban road maintenance?" It outlines the multi-phase approach undertaken, which combines Geographic Information Systems (GIS)-based spatial suitability analysis with network configuration modeling and evaluation. The chapter will describe the research design, the definition of the study area, the data sources and analytical tools utilized, and the specific procedures followed in each phase of the research: identifying potential locations for main Circular Construction Hubs (CCHs), selecting sites for Temporary Storage Sites (TSS) within a Hub-and-Spoke paradigm, and comparatively analyzing different logistics network configurations. The methods described herein provide the foundation for the results and subsequent discussion presented in later chapters.

3.2. Design Science Research

Design Science Research (DSR) is a problem-solving paradigm that seeks to create and evaluate innovative artifacts (including constructs, models, methods, and instantiations) intended to solve identified organizational or real-world problems (Hevner et al., 2004). This study adopts the Design Science Research Methodology (DSRM) as formalized by Peffers et al. (2007). This framework provides a nominal process model for conducting and communicating the research.

The DSRM consists of six primary activities. While presented as a nominal sequence, the process is often iterative, with researchers cycling back to earlier steps as the project evolves. Figure 3.1 provide visual representation of the process model.

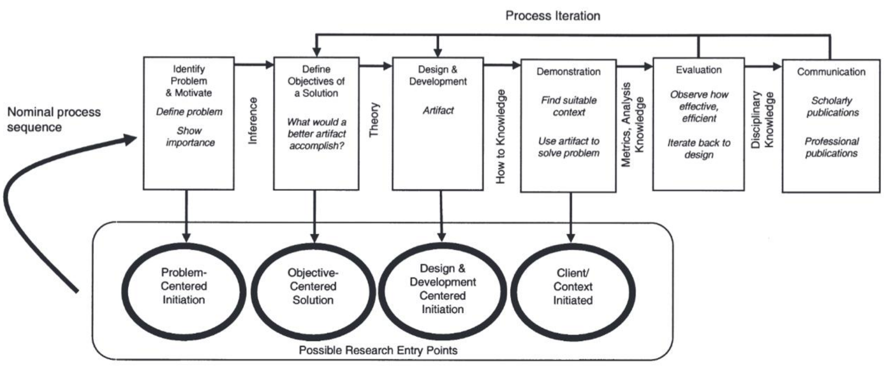


Figure 3.1: DSR framework (adapted from Peffers et al. (2007).

The description of each activity is described as follows:

1. **Activity 1: Problem Identification and Motivation**
   The process begins by defining the specific research problem and justifying the value of a solution. This involves demonstrating the problem's importance and building a strong case for pursuing a novel solution.
2. **Activity 2: Define the Objectives for a Solution**
   The objectives are inferred from the problem definition. They should be framed in a way that is both achievable and measurable, specifying what a successful artifact would accomplish. These objectives form the basis for the subsequent evaluation of the designed artifact.
3. **Activity 3: Design and Development**
   This is the core activity of creating the research artifact. The artifact's design should be informed by existing theories, and its development involves determining the desired functionality and architecture and then building the artifact itself. In this thesis, the artifact is a set of models and a decision-making framework.
4. **Activity 4: Demonstration**
   The designed artifact is used to solve an instance of the problem. This can be done through experimentation, simulation, case study, or other appropriate methods, serving as a proof-of-concept that the artifact works.
5. **Activity 5: Evaluation**
   The performance of the artifact is observed and measured. This involves comparing the results from the demonstration against the objectives defined in Activity 2. The evaluation provides evidence of the artifact's utility and rigor. Based on this evaluation, the researcher may iterate back to Activity 3 to refine the artifact.
6. **Activity 6: Communication**
   The problem, artifact, its utility, and its evaluation are communicated to a relevant audience. This includes scholarly publications that contribute to the knowledge base and professional communications that contribute to practice.

Peffers et al. (2007) also recognize that DSR projects do not always start at the first activity. They identify four possible "entry points" into the DSRM cycle. This thesis follows a Problem-Centered Initiation, which is an appropriate entry point when the research is triggered by the observation of a significant, real-world problem that requires a novel solution. As detailed in Sections 1.1 and 1.2 of this thesis, the research was directly motivated by the identified challenges in achieving Amsterdam's circularity goals, specifically the logistical inefficiencies and high transport costs associated with reusing road maintenance materials.

Having established DSRM as the guiding framework, the remainder of this thesis will follow its structure. The next chapter will not reiterate this framework but will instead detail the specific application of these six activities to the problem of siting CCHs in Amsterdam. It will describe the concrete steps taken to design the evaluation models, the metrics used to define the objectives, and the process for demonstrating and evaluating the resulting network configurations.

3.3. Research Approach

This research follows the Design Science Research Methodology (DSRM) paradigm, focusing on the creation and iterative evaluation of a purposeful artifact. The primary artifact of this research is a multi-component, quantitative framework for strategic logistical planning, designed to be a practical and transferable tool for urban planners and policymakers.

The entire research process is structured as a series of interconnected activities, as visualized in the DSRM flowchart (Figure 3.2). The process moves from a foundation phase, where the problem and objectives are defined, through a multi-loop process of design and evaluation, resulting in the communication of a final, refined artifact. A key feature of this approach is its iterative nature, which involves two distinct evaluation loops: a quantitative loop to achieve quantitative optimization, followed by a qualitative loop to ensure real-world feasibility.

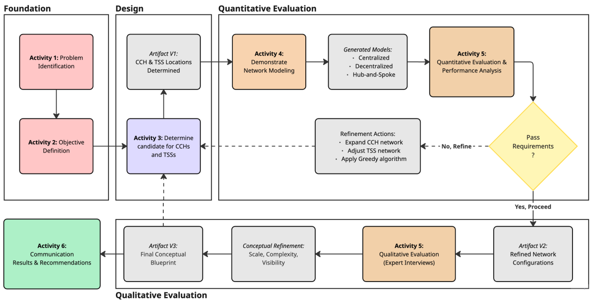


Figure 3.2: Adapted DSRM framework flowchart.

Phase 1: Quantitative Evaluation

The first phase of the research involves a quantitative design cycle. This process begins with an Initial Design (Activity 3), where a GIS-based suitability model is used to identify an initial set of candidate locations for CCHs and TSSs (Artifact V1). This initial network is then subjected to a Demonstration (Activity 4), where a set of network configuration models (Centralized, Decentralized, and Hub-and-Spoke) are used to simulate material flows.

The performance of these models is then assessed in a Quantitative Evaluation (Activity 5) against a set of formal performance requirements (R-1, R-2, R-3). As the initial artifact failed this evaluation, the DSRM process entered a refinement loop. This Re-Design phase involved applying targeted refinement actions, such as expanding the CCH network and employing a custom-developed Greedy Heuristic algorithm, to create a set of refined network configurations (Artifact V2). This refined artifact successfully passed the quantitative evaluation, concluding the computational phase of the research.

Phase 2: Qualitative Evaluation

The second major phase, takes the quantitatively optimized artifact (V2) and subjects it to a qualitative evaluation. This Qualitative Evaluation (Activity 5) involves a series of semi-structured interviews with industry and municipal experts to assess the artifact's practical feasibility against the real-world constraints of Amsterdam.

The insights from this expert evaluation are used to identify key gaps between the optimized model and practical reality, focusing on themes like spatial scale, operational complexity, and socio-cultural visibility. This analysis informs a final Conceptual Refinement, where the insights are synthesized to create the final, most robust version of the artifact: a Final Conceptual Blueprint (Artifact V3). This written blueprint represents the result of the entire DSRM process, integrating both quantitative optimization and qualitative, real-world insights. The final artifact and the principles derived from its creation are then formally reported in the final chapters of this thesis (Activity 6: Communication).

3.4. Activity 1 & 2: Foundation

The DSRM process is initiated by establishing a clear problem and a set of measurable objectives. These foundational activities precede the main design cycle and are detailed below.

3.4.1. Problem Identification

As explained in previous chapters, the main issue involves two connected challenges. First, the construction sector, especially road infrastructure, plays a major role in resource consumption and CO_2 emissions. Second, although cities like Amsterdam have set ambitious circular economy goals, the systems needed to enable high-value material reuse are not yet fully developed. In particular, the collection, consolidation, and redistribution of secondary materials such as concrete tiles and bricks face several logistical obstacles. These include long transport distances from scattered project sites, a shortage of suitable storage space, and mismatches between supply and demand. These inefficiencies increase both costs and environmental impact, making it harder to achieve circularity targets.

This gap between policy ambitions and on-the-ground implementation highlights the need for a structured and data-driven approach. Therefore, the motivation for this research is to design a practical tool that can support strategic decisions on where to locate and how to organize the necessary logistical infrastructure, referred to as Circular Construction Hubs (CCHs), to improve material reuse.

3.4.2. Objective Definition

To quantitatively assess and compare the logistical performance of the different CCH network configurations, a set of clearly defined and relevant key performance metrics was used. The selection of these metrics was guided by their ability to capture the primary transport effort involved in moving materials, their alignment with established industry practices and international frameworks. The following subsections detail the primary metrics employed in this study: total routed distance, total tonnage handled, and total tonne-kilometers, along with the assumptions applied in their calculation and interpretation.

Distance

The primary measure of spatial extent for material movements in this study is network distance, calculated in kilometers (km). This represents the shortest feasible path along the established road network between an origin point (material source) and a destination point (CCH or TSS), or between two intermediate facilities (e.g., TSS to CCH). All distance calculations were performed using an Origin-Destination (OD) Cost Matrix tool using QNEAT3 plugin for QGIS.

Tonnage

The total tonnage handled (t) represents the annual mass of material (concrete tiles and bricks) recovered from road maintenance projects and moved through the logistics network in each scenario. The estimation of tonnage for each project site was derived from municipal project data, which provided the surface area (m^2) of intervention. To convert this area to mass, the following assumptions were applied consistently across all calculations:

1. An average material thickness of 0.07 meters (7 centimeters) was assumed for all target paving elements. This value is based on typical dimensions for materials like *betontegels* used in Amsterdam, particularly considering an average between standard (4.5 cm) and heavy-duty (8 cm), and accounting for some associated bedding material (Gemeente Amsterdam, 2024).
2. An average material density of 2400 kilograms per cubic meter (kg/m^3) was utilized. This figure is a standard estimate for concrete-based materials and was applied for simplification across the target material stream of concrete tiles and bricks (López López et al., 2023).

Based on these assumptions, the tonnage for each individual project segment was calculated using the formula:

$$\text{Tonnage (t)} = \frac{\text{surface area (m}^2\text{)} \times \text{thickness (m)} \times \text{density (kg/m}^3\text{)}}{1000\,\text{(kg/t)}} \tag{3.1}$$

Tonne-kilometers

One of the principal metric for evaluating and comparing the logistical efficiency of the different network configurations was total system tonne-kilometers (t-km). A tonne-kilometer, representing the transport of one tonne of goods over one kilometer, is a standard unit in logistics and transport statistics that quantifies freight transport volume in terms of physical work accomplished (Rodrigue, 2024). It aggregates both the weight of cargo and the distance it is moved into a single, comparable metric, calculated as:

$$\text{Tonne-kilometers (t-km)} = \sum_i (\text{tonnage}_i \times \text{distance}_i) \tag{3.2}$$

where tonnage_i is the mass of material for a given movement i, and distance_i is the network distance traveled for that movement. The calculation methodology adheres to ISO 14083:2023, where t-km for each transport leg is the product of the mass transported. For multi-leg shipments, the t-km for each segment the cargo travels is summed (see Appendix A).

The Global Logistics Emissions Council (GLEC) Framework V3.0 (in accordance with ISO 14083:2023) mandates the calculation of transport activity in t-km as the foundational first step in emissions accounting (Smart Freight Centre, 2024), which enables consistent comparisons and forming the basis for emissions calculations (by applying emission factors per t-km). However, this can lead to situations where a network designed for higher material recovery or more efficient vehicle utilization might not strictly minimize total t-km for every individual item,

Therefore, while t-km is employed in this study as one of the primary quantitative metric for comparing the overall transport effort of different network configurations, the analysis acknowledges that it is one component of a broader assessment. The t-km results will be interpreted in the context of the network's structural ability to facilitate material consolidation, considering the number and placement of CCHs and TSS, and the resulting tonnage flows.

Rationale
Overall, this study evaluates a network configuration on the basis of three descriptive indicators:

1. **Total distance (km):** the summed one-way kilometer length of all legs in each layout;
2. **Total tonnage handled (t):** the annual mass of material moved (identical in every layout); and
3. **Tonne-kilometers (t-km):** the leg-by-leg product of tonnes and routed kilometers, aggregated in accordance with the GLEC/ISO definition of transport activity.

These metrics are chosen because they are (a) directly observable from location data, and (b) recognized by the GLEC Framework as the minimum information set required to quantify transport work without additional modeling assumptions.

Using this triad also aligns with the measurement conventions embedded in European policy and industry practice. Carbon-accounting schemes such as the ECTA/Cefic guidelines adopt t-km as the activity base to which mode-specific emission factors are applied, while simultaneously reporting absolute tonnes and kilometers to ensure transparency (Cefic & ECTA, 2011). The International Transport Forum likewise relies on tonne-kilometres when modeling national and urban freight scenarios, precisely because it aggregates the raw inputs into a statistic that is directly comparable across modes and regions (International Transport Forum, 2023).

From a data standpoint, distance and weight are routinely captured by transport-management and telematics systems, whereas more elaborate metrics such as vehicle-kilometers or payload utilization require extra assumptions about empty running and capacity (Hinkamp & Ismael, 2023). Basing the analysis on these primary, auditable variables therefore minimizes uncertainty and keeps the methodological workload light, which is important when the thesis must compare several network scenarios.

Analytically, the three metrics are sufficient to feed both cost- and carbon-optimization models. Linear and mixed-integer network formulations typically include a term that multiplies tonnes by routed distance; solving for the minimum of that term directly yields the least-t-km, and often least-cost, configuration without needing supplementary traffic indicators (Hinkamp & Ismael, 2023). Because variable transport cost and well-to-wheel CO_2 are usually priced per t-km, the same optimization results can later be re-expressed as €/t-km or g CO_2/t-km without re-running the model.

All other operational variables (e.g, vehicle type, fuel, payload utilization, empty running, service windows, labor hours and cost structures) are held constant for the purpose of the calculation. As a result, the numerical comparison that follows indicates which network geometry minimizes distance and transport work, given equal operational conditions.

The potential impact of varying those additional factors will be examined qualitatively in Chapter 5; they are not included in the quantitative calculation so as to keep the focus on hub location efficiency and to avoid overstating precision when no primary data on vehicle utilization are available.

3.5. Activity 3: Initial Design

The core of the DSRM process is the design and development of the research artifact. This activity involves creating the artifact's components, which in this study are the models and processes that form the strategic siting framework. This section details the initial design of these components and the process for their subsequent refinement, which constitutes the DSRM ”redesign” loop.

3.5.1. Scope

The geographical focus of this study is the City of Amsterdam, the capital and most populous municipality of the Netherlands. A map illustrating the administrative boundaries of the city, which account for the study area for all spatial analysis and network configuration, is provided in Figure 3.3.

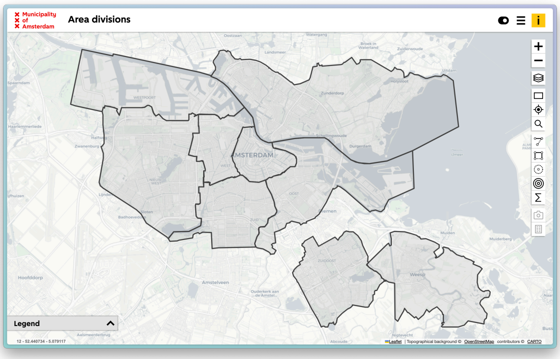


Figure 3.3: Geographical scope of this study (source: Municipality of Amsterdam).

The selection of this city as the case for this study of strategic location and configuration of CCH for road maintenance materials is based on several factors: the city proactive circular economy policies, the specific characteristics and significant volume of its road maintenance material flows, and its dense urban structure which presents unique logistical challenges. A comprehensive elaboration of these contextual elements and the detailed rationale for the city as the case study already presented in Section 2.6. Therefore, all methodological procedures detailed hereafter were applied within the defined geographical limits of the City of Amsterdam.

3.5.2. Tools

Several key datasets were acquired to facilitate the suitability analysis, network configuration modeling, and evaluation of CCH and TSS configurations:

- **OpenStreetMap (OSM):** OSM served as a fundamental source for geospatial data used in this study. Specifically, land use polygons were extracted from OSM to identify potential areas for CCH and TSS development and to delineate constraint areas. The road network layer, also obtained from OSM, provided a detailed representation of streets, roads, and pathways, including attributes such as road type and hierarchy. The open and frequently updated nature of OSM makes it a valuable resource for urban studies, although it requires careful validation where appropriate. The definitions of these land uses were extracted from OpenStreetMap Wiki.
- **Road maintenance project data:** a dataset detailing planned road maintenance projects within the City of Amsterdam for the period 2025-2030 was obtained from municipality. This dataset contains attributes for each planned maintenance, including project types, the materials involved, planned start and end years, location identifiers, and, importantly, the surface area (in m^2) of each project segment. For this study, projects involving the target materials (concrete tiles and bricks) were used.

The processing, analysis, and visualization of spatial and tabular data were conducted using the following tools:

- **QGIS:** an open-source Geographic Information System, was the primary software environment for most geospatial tasks.
- **QNEAT3 Plugin (for QGIS):** QNEAT3 (QGIS Network Analysis Toolbox 3) plugin was specifically employed for all network distance calculations and Origin-Destination (OD) Cost Matrix generation. This tool facilitated the calculation of shortest path distances along the prepared OSM road network between sets of origin points (material sources) and various destination points (candidate CCHs and TSS).

- **Python:** the python language used within Visual Studio Code and Jupyter Notebooks was utilized for data processing, analysis, and visualization.

Across the various analytical phases, several standard geospatial operations were consistently applied. These included, but were not limited to, buffering (to create zones of influence or exclusion around features), spatial overlay analysis (e.g., intersection, union, erase to combine or subtract information from different layers), area and distance calculations, and centroid generation (to represent polygon features as points for network analysis). Moreover, to ensure spatial accuracy and consistency across all datasets and analyses, a standard projected coordinate system was employed. All geospatial data were either natively in, or projected to, EPSG:28992 - Amersfoort / RD New, which is the official coordinate system for the Netherlands.

3.5.3. Suitability: CCH

The primary objective of this initial phase was to identify spatially feasible candidate locations for the establishment of main Circular Construction Hubs (CCHs) within the Amsterdam study area. This was achieved through a GIS-based suitability analysis that integrated various land use constraints and assessed proximity to road maintenance project clusters, which are the primary sources of materials for this study. The criteria for site selection were informed by the operational needs of CCHs and the imperative to minimize conflicts with existing urban functions, as detailed in the previous chapter.

The identification of candidate CCH locations within Amsterdam was guided by a set of suitability criteria derived from the broader range of factors identified in the literature (as discussed in Subsection 2.4.5), but specifically adapted and filtered to suit the urban context of Amsterdam, the nature of CCHs for road maintenance materials, and the available geospatial data. Given the strategic, city-wide scope of this initial screening, the focus was on applying clear, impactful criteria that could effectively delineate potentially suitable zones from unsuitable ones, rather than employing a complex multi-criteria weighting system at this stage. The selected criteria, along with their operationalization and rationale, are outlined below:

Table 3.1 provides a summary of the selected criteria and their specific operationalization for this study. The rationale behind each is detailed below:

Table 3.1: Selected criteria for methodology.

Criterion	Thresholds	Literature
Land-use compatibility	Boolean filter	Akther et al. (2019), Alqahtani et al. (2024), Cobos-Mora et al. (2023), Demesouka et al. (2016), Donevska et al. (2021), Loureiro et al. (2023), Nuhu et al. (2022), Özkan et al. (2019), and Shahparvari et al. (2020)
Minimum parcel area	≥ 1 ha (10 000 m²)	Tsui et al. (2023)
Exclude incompatible uses	Absolute mask	Akther et al. (2019) and Donevska et al. (2021)
High-sensitivity buffer	250 m no-go zone	Akther et al. (2019), Cobos-Mora et al. (2023), Donevska et al. (2021), Loureiro et al. (2023), and Shahparvari et al. (2020)
Low-sensitivity buffer	100 m no-go zone	Akther et al. (2019), Ding et al. (2018), Donevska et al. (2021), and Loureiro et al. (2023)

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Criterion	Thresholds	Literature
Proximity to sources	≤ 3 km preferred	Demesouka et al. (2016), Ding et al. (2018), Donevska et al. (2021), and Tsui et al. (2023)

The rationale for each criterion and threshold summarized in Table 3.1 is detailed as follows:

1. **Land use compatibility**
   Candidate locations were required to be situated on land designated for uses compatible with CCH operations. This included sites zoned as industrial, logistics, depot, and storage areas, as well as identified brownfield sites, based on OpenStreetMap (OSM) land-use data.

   This foundational criterion aligns with extensive literature (Akther et al., 2019; Cobos-Mora et al., 2023; Nuhu et al., 2022) emphasizing the need for CCHs to be located in areas where their industrial/logistical nature minimizes conflict with other urban functions and can leverage existing infrastructure. Open/industrial land is consistently ranked highly for suitability.

2. **Minimum parcel area**
   Only land parcels meeting or exceeding 1 hectare were considered for CCHs. This threshold, informed by literature on various hub types (Tsui et al. (2023) noting urban mining hubs at 5 ha and craft hubs ≥ 1200 m²), was chosen to ensure sufficient space for essential CCH activities such as material handling, storage, potential basic sorting, and associated logistical movements (vehicle maneuvering, parking). While larger industrial hubs in literature are often 10-30 ha, a 1-hectare minimum was deemed a practical starting point for CCHs within a dense urban environment like Amsterdam. This threshold serves as a practical starting point for a major hub in a dense urban environment. As will be further explored in the discussion, municipalities themselves are often best positioned to determine ideal land size requirements based on local planning documents and land availability.

3. **Exclusion of incompatible land use & buffers**
   Fundamentally incompatible land uses (e.g., military installations, active landfills, existing major construction sites identified in OSM) were entirely excluded. A buffer of 250 meters was applied around land uses considered highly sensitive to potential disturbances from CCH operations. These included residential areas, allotments, educational facilities, cemeteries, recreation grounds, village greens, and designated parks. Candidate CCHs could not be located within these buffered zones. A 100-meter buffer was applied around areas with lower, but still notable, sensitivity, such as retail areas, meadows, commercial zones, and farmland.

   These exclusion criteria are standard practice in site suitability literature (Akther et al., 2019; Donevska et al., 2021). The buffer distances were adapted from general ranges found in literature (Akther et al., 2019; Ding et al., 2018). The 250 m and 100 m values were chosen as pragmatic initial screening distances for the Amsterdam context to minimize direct conflicts while not being overly restrictive at a city-wide scale.

4. **Proximity to material source clusters**
   While not a hard exclusion, proximity to clusters of planned road maintenance projects (the primary material sources) was a key consideration. An effective operational radius of up to 3 kilometers from source locations was considered preferable. This was used to classify preliminary candidate cells (near, medium, far within the 3 km radius) rather than as an initial filter.

   This aligns with literature emphasizing the importance of locating facilities near waste/material generation centers to reduce initial transport distances and enhance logistical efficiency (Ding et al., 2018; Tsui et al., 2023). For CCHs focused on road maintenance, proximity to planned project areas is critical. The 3 km threshold was based on Tsui et al. (2023) for effective CCH operational radius.

Several criteria identified in the broader literature were not directly applied as numerical filters in this initial GIS screening phase for specific reasons:

- **Detailed geophysical criteria**
  In a relatively flat and highly urbanized/engineered environment like Amsterdam, these factors are less differentiating for initial site identification at a strategic level, especially when focusing on existing industrial/brownfield land.
- **Road network access**
  This is criteria was not applied because industrial zones with a substantial parcel size (≥ 1 hectare) already ensures good road access in Amsterdam, where they are typically near major roads. Adding a separate road access filter would be redundant and could exclude suitable sites unnecessarily.
- **Economic factors**
  While crucial for final implementation, land price data at a consistent, granular level suitable for city-wide GIS screening was not readily available for this study.

The analytical framework was established by generating a 100x100 meter resolution grid across the study area to evaluate suitability. Next, land use data was used to identify parcels that met the appropriate land use criterion and those categorized as sensitive or excluded. In addition, maintenance projects data from the municipality were aggregated into cluster centroids to represent discrete material source locations for the proximity analysis. The implementation of the suitability criteria involved several sequential geospatial operations:

1. The OSM land use data was filtered to select parcels aligning with the 'Appropriate Land Use' criterion. From this subset, only parcels meeting the sufficient size criterion (≥ 1 hectare) were retained, forming a layer of potentially suitable large land parcels.
2. The 'Sensitive' land use categories (high and low sensitivity, parks) were buffered according to the distances specified in the criteria (250m and 100m, respectively). These buffered zones, along with the 'Directly Excluded Land Uses,' were compiled into a comprehensive constraint map.
3. Each cell in the 100x100m analysis grid was then evaluated. A cell was flagged as a preliminary candidate CCH location if it:
   - Spatially intersected with one of the identified suitable large land parcels, and
   - did not spatially intersect with any area within the comprehensive constraint map (i.e., it was outside all buffered sensitive zones and directly excluded areas).
4. The preliminary candidate CCH locations were further analyzed based on the 'Proximity to Material Sources' criterion. An operational radius of up to 3 kilometers from these sources was considered preferable for minimizing initial transport burdens.

Figure 3.4 visualizes these criteria translated into suitability layers for GIS analysis.

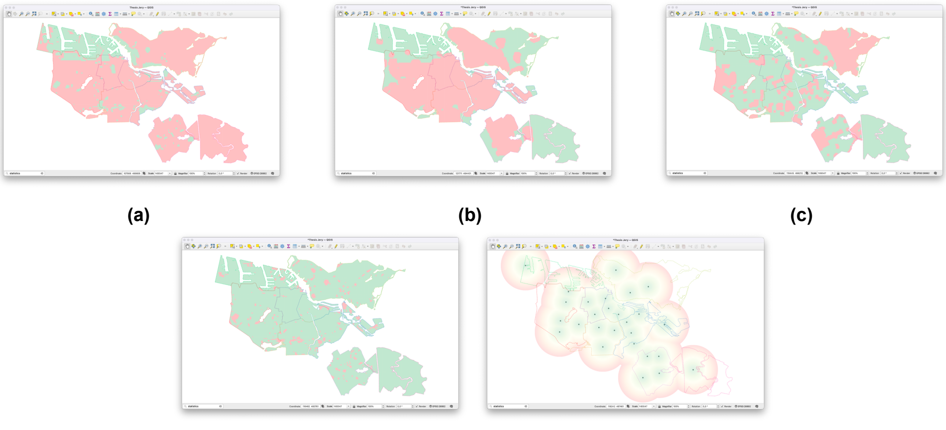


Figure 3.4: GIS suitability layers: (a) compatible land use & size, (b) high-sensitivity buffer, (c) low-sensitivity buffer, (d) exclusion area, and (e) proximity to sources.

Based on this distance, candidate cells were classified (e.g., 'Near', 'Medium', 'Far') if they fell within the 3-kilometer desirable radius. This classification provided an additional layer of information regarding the logistical advantages of each potential site.

The output was a comprehensive geospatial dataset, represented by the analysis grid. This dataset delineated all 100x100 m cells within Amsterdam, indicating for each its compliance with the defined criteria for land use, parcel size, and avoidance of constraints, thereby flagging it as either a candidate CCH grid cell or not.

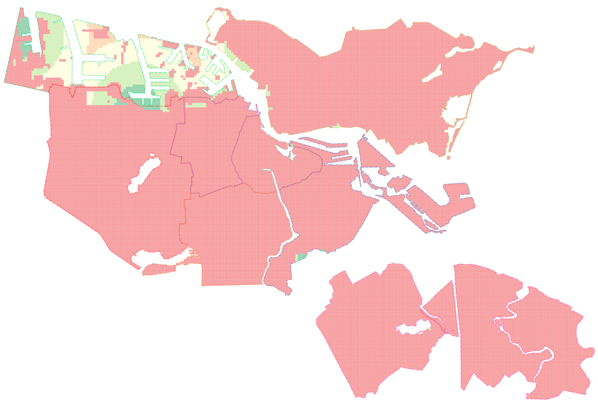


Figure 3.5: Suitability analysis results: candidate areas classified from not suitable (red) to near (green).

Clusters of contiguous, highly-ranked (e.g., 'Near' or 'Medium' proximity, and meeting all suitability criteria) candidate grid cells (Figure 3.5) were identified, visually inspected, and then cross-referenced with satellite imagery (Google Maps). These steps are necessary to confirm that the areas represented by the suitable grid cell clusters indeed corresponded to established industrial or logistical zones with characteristics suitable for CCH operation.

Based on this combined GIS output review and visual verification, a preliminary three locations were selected as the final candidate CCH locations for further analysis:

1. The industrial area in Havens-West, Westpoort.
2. The industrial area in Noordelijke IJ-oevers-West, Oud-Noord, Noord.
3. The industrial area in Omval/Overamstel, Watergraafsmeer, Oost.

Alternative locations which also matched suitability criteria, such as Noordelijke IJ-oevers-Oost (lack access to arterial roads) and the far west of Havens-West (too far from clusters of maintenance sites), were considered not passing these preliminary stages. The locations selected in this phase were shown in Figure 3.6, represented as star points.

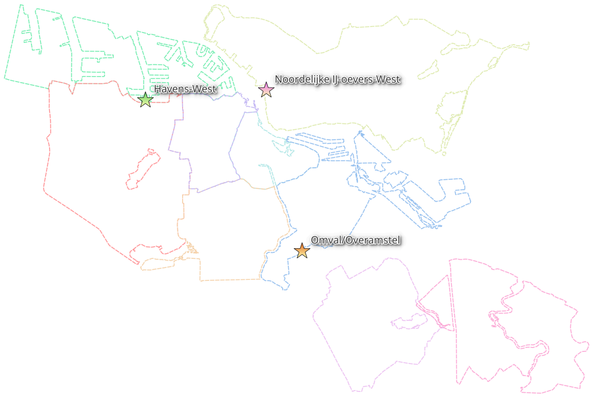


Figure 3.6: Candidate CCH locations shown as star icons across Amsterdam.

These preliminary CCH locations would later be tested in network configuration analysis to understand the effect of the siting in the whole logistical network.

3.5.4. Suitability: TSS

Complementary to identifying main CCHs, this phase focused on identifying and selecting a strategic set of potential Temporary Storage Sites (TSS). These TSS are conceptualized for use within a Hub-and-Spoke network configuration (detailed in Subsection 3.6.3, serve as intermediate consolidation points for road maintenance materials. The selection process involved several stages, starting with broad suitability screening across the study area, followed by manual validation, and culminating in a targeted selection of TSS based on their spatial relationship to material sources and CCH service areas.

Potential TSS locations were first identified from a land use layer based on broad suitability criteria. Land uses such as industrial, logistics, depot, brownfield, and storage were considered. A key differentiator was the area threshold: selected parcels were required to be between 100 m^2 and 10,000 m^2 (1 hectare), ensuring sites were large enough for basic operations but distinct from larger CCH facilities. During this automated screening, explicit constraints for proximity to the general road network or buffers around sensitive land uses were omitted, prioritizing the capture of a wide initial set of candidates. However, an exclusion zone of 500 meters (in euclidean distance) around the candidate CCH locations was applied to prevent spatial overlap and ensure distinct functionalities.

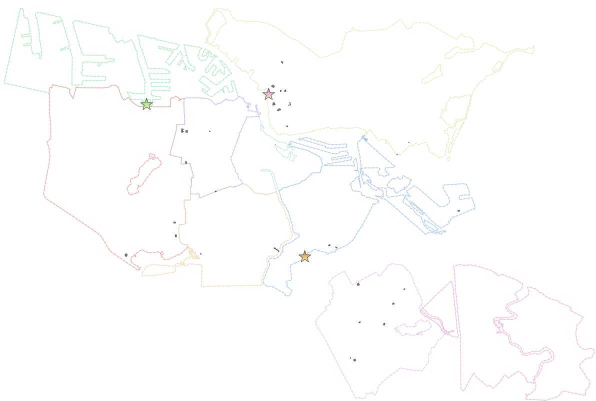


Figure 3.7: Preliminary result showing identified small TSS land parcels.

The output from the initial screening then validated. Each candidate TSS parcel was visually inspected against contemporary satellite imagery and street-view data in Google Maps. This step involved removing candidates found to be clearly unsuitable upon visual inspection (e.g., occupied by incompatible structures, demonstrably inaccessible, or actively used for conflicting non-industrial purposes). This process resulted in several filtered land parcels, as shown in Figure 3.7.

The subset of TSS from initial screening was then selected for direct use in the initial Hub-and-Spoke network model scenario. This targeted selection aimed to identify TSS strategically positioned to effectively serve clusters of material sources and integrate with the service areas of the main CCHs.

First, centroids of clustered road maintenance projects (representing material source concentrations) were identified. Service areas were then generated around these centroids by routing one kilometers along the road network (for visual clarity), delineating zones in close proximity to material origins. Similarly, service areas were generated around the primary CCH locations by routing three kilometers along the road network (Tsui et al., 2023), representing zones reasonably serviceable by each CCH (see Figure 3.8).

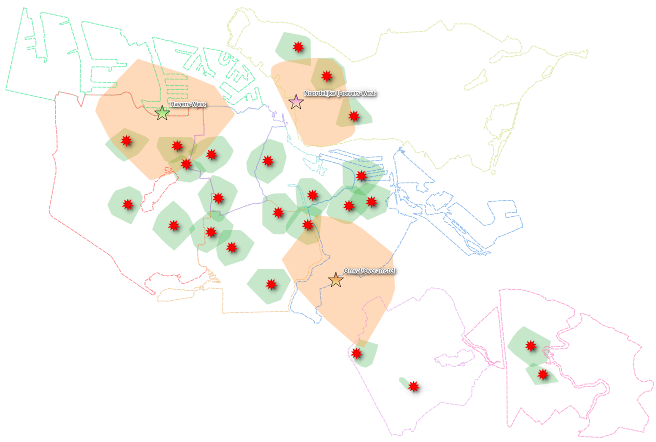


Figure 3.8: Service (catchment) area of CCH (3 kilometers) in orange, and project clusters (1 kilometers) in green.

Therefore, candidate locations for TSS were selected if they located within or in close proximity to:

- the material source clusters,
- the 3 kilometers service areas of CCHs,
- arterial roads for transport connectivity, and
- land use types deemed suitable for TSS operations.

The primary output of Phase 2 was this selected set of eight TSS locations. These sites, identified through a multi-stage process of GIS suitability screening, validation, and spatial-relational selection, formed the specific intermediate consolidation points used in the construction and initial evaluation of the Hub-and-Spoke network model detailed in Subsection 3.6.3. This approach ensured that the TSS incorporated into the hub-and-spoke network were not only generally suitable for storage but also strategically located to potentially enhance the efficiency of material collection and transfer within the network.

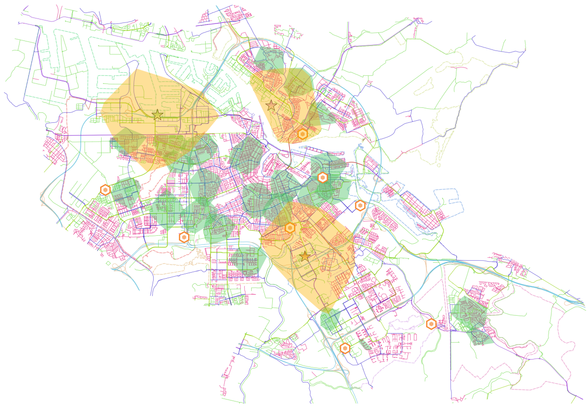


Figure 3.9: Eight identified candidate locations for TSS represented in orange hexagon points.

3.6. Activity 4: Demonstration

The demonstration activity in DSRM involves applying the designed artifact to a specific instance of the problem to illustrate its utility and functionality. In this study, the demonstration was executed by applying a set of network configuration models to the initial CCH and TSS locations that were identified in the design phase (Activity 3). This process serves to demonstrate the artifact's core capability: generating and assessing distinct logistical scenarios based on real-world data from the Amsterdam case.

A critical aspect of this demonstration is the defined scope of the analysis. A complete circular system involves both a reverse logistics flow (collecting used materials from project sites) and a forward logistics flow (distributing reusable materials to new project sites). This study's primary objective is to solve the strategic spatial problem of where to locate the necessary infrastructure. To do this effectively, the analysis focuses specifically on optimizing the reverse logistics flow: the journey of salvaged materials from their source at a road maintenance project, potentially via a Temporary Storage Site (TSS), to a final Circular Construction Hub (CCH).

This focus is a deliberate methodological choice. Modeling the forward flow would introduce a different set of complexities, primarily time-based demand and facility capacity constraints (e.g., if a TSS is full, or if a project only needs materials on a specific day). Such an analysis would require dynamic operational simulation rather than the strategic spatial analysis that is the core of this thesis.

Therefore, the following network models are designed to find the most efficient spatial configuration for collecting and consolidating secondary materials, providing the foundational network blueprint upon which a complete circular system can be built. The performance of these models is evaluated based on the total transport effort required to move all salvaged materials from their source to a final processing hub.

The demonstration was carried out by modeling three distinct logistical strategies. These models were applied to the set of initial CCH and TSS sites using the project data from the Amsterdam context. The purpose of running these models is to generate the baseline performance data that will be analyzed in the Evaluation phase (Activity 5).

Note: *the following figures for each network configuration use Euclidean distances for visual clarity only; actual calculations were based on routed road network distances. Additionally, the nodes shown are for demonstration purposes only, and the actual nodes will be implemented in later stages.*

3.6.1. Centralized Network

This configuration represents the most basic network structure, assuming all road maintenance materials are transported directly from maintenance projects to a single CCH. To implement this, the shortest network distance was calculated from each material source point (origin) directly to this selected centralized CCH (destination) using an Origin-Destination (OD) Cost Matrix. Figure 3.10 illustrates how the materials flow from several source points to one centralized node in this configuration. Note that the figure uses euclidean distances only for visual clarity, but the real calculations were using routed road network.

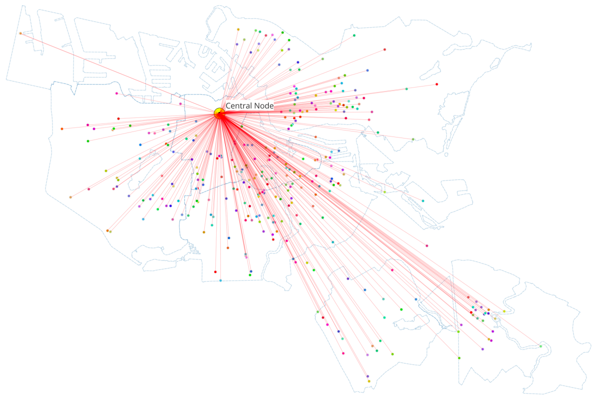


Figure 3.10: Materials flow from several source nodes into central node in euclidean distances.

The resulting distances and associated tonnages were then used to calculate the total tonne-kilometers for this baseline configuration. Total distance from all source points to the three CCH candidates identified were calculated and compared.

3.6.2. Decentralized Network

The Decentralized configuration explores the impacts of distributing CCH facilities across the study area, allowing for potentially shorter travel distances. The core principle is that materials from each source point are transported to the geographically nearest available CCH from a defined set of active CCH locations. Figure 3.11 shows the simplified version of how the material from several source points into several central nodes in this configuration.

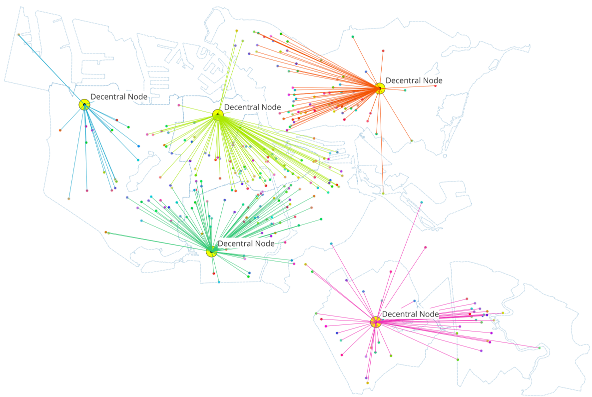


Figure 3.11: Materials flow from several source nodes into several central nodes in euclidean distances.

The implementation involves using an OD Cost Matrix to calculate the shortest network distance from each material source point to all active CCHs in the defined set. For each source point, the material flow is allocated to the CCH for which this calculated shortest path distance is minimized. This process determines the catchment area and material throughput for each CCH in the decentralized network, allowing for the calculation of overall system tonne-kilometers and other performance indicators.

3.6.3. Hub-and-Spoke Network

The Hub-and-Spoke scenario evaluates a two-stage logistics system that incorporates potential intermediate consolidation at TSS facilities. Figure 3.12 shows the basic principle of this configuration, where materials flow into consolidation points before reaching the final destinations.

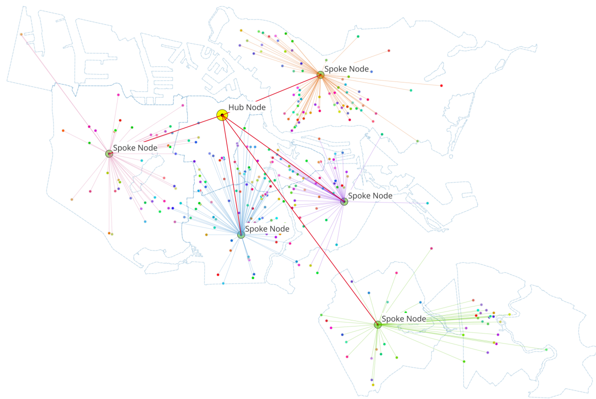


Figure 3.12: Materials flow to consolidate in spoke nodes before going to the hub node in euclidean distances.

For this study, this configuration used hybrid routing logic: materials from a source point are routed to the nearest active TSS only if the network distance to that TSS is shorter than the direct network distance to the nearest active CCH; otherwise, materials flow directly from the source to the nearest active CCH. For materials consolidated at a TSS, a second transport leg moves these materials from the TSS to the nearest active CCH.

The implementation of this scenario involves several analytical steps using OD Cost Matrices. First, for each material source point, shortest network distances are calculated to all active CCHs and to all active TSS (selected from the Phase 2 candidates). The "if nearer" routing rule is then applied to assign each source's material flow to either its Leg 1 journey (Origin-to-TSS) or a direct Origin-to-CCH path. For all materials assigned to a TSS, the shortest network distance for Leg 2 (TSS-to-nearest-CCH) is then determined. To accurately reflect the transport effort for consolidated movements, the Leg 2 distances are typically weighted by the volume or number of source trips consolidated at each TSS when calculating overall system tonne-kilometers (a detailed explanation of this two-leg distance calculation and weighting is provided in Appendix A). The total system performance is then aggregated from all direct-to-CCH flows and the combined Leg 1 and Leg 2 flows of the network paths.

3.7. Activity 5: Evaluation

The evaluation of the designed artifact is a critical, multi-stage process within the DSRM framework. It is the activity that assesses the performance and utility of the network configurations, determining whether they are satisfactory solutions or require further refinement. This thesis employs a two-phase evaluation approach: a quantitative evaluation to assess the models' logistical performance and operational viability, followed by a qualitative evaluation to assess their real-world feasibility.

3.7.1. Quantitative Evaluation

A set of three quantitative evaluation requirements was designed. As visualized in the flowchart's decision diamond, if a modeled configuration violates one or more of these requirements, it is deemed unsatisfactory, triggering the "No - Refine" path and necessitating the application of the redesign methods. The rules are summarized in Table 3.2 and detailed below.

Table 3.2: Network design requirements.

Req. ID	Req. Name	Purpose	Trigger
R-1	Hub Balance	Prevent any single CCH from becoming an operational bottleneck	Shares of total t-km $>$ 40%
R-2	Spoke Efficiency	Ensure the entire TSS network is efficient	Fails if all are true: • km/t $>$ 6 • km/project $>$ 8 • tonne-share $<$ 10%
R-3	Network Coverage	TSS coverage in the system	Tonnes $<$ 90% of total

R-1: Hub Balance

This requirement is designed to prevent any single CCH from becoming an operational bottleneck. It measures the share of total system tonne-kilometers handled by the busiest hub. A configuration is considered imbalanced if the share of the largest hub exceeds 40%. The formula to calculate this requirement is:

$$\text{Hub-share}_i = \frac{\text{t-km}_i}{\sum_j \text{t-km}_j} \tag{3.3}$$

R-2: Spoke Efficiency

This requirement ensures that every active TSS (spoke) in the network contributes efficiently to the overall consolidation effort. An individual TSS is considered a point of systemic failure if it creates an excessive transport burden without handling a significant volume of material.

The entire Hub-and-Spoke network configuration is deemed unsatisfactory and requires a redesign if even one of its active TSS fails the following three sub-tests simultaneously:

- **km/t:** (Leg 1 t-km + Leg 2 t-km) / tonnes > 6 km/t
- **km/project:** (Leg 1 km + Leg 2 km) / projects > 8 km/project
- **tonne-share:** tonnes / total system tonnes < 10 %

This benchmark is established by first running the baseline Centralized model, which represents the direct hauling in this study. As will be detailed in the results, this baseline model resulted in an average travel distance of 5.48 km per trip. The 6 km/t threshold is set approximately 10% above the 5.48 km baseline. This tolerance acts as a ”no significant harm” test, flagging a TSS as inefficient only when its negative impact on transport effort becomes significant. The 8 km/project threshold is set approximately 50% above the baseline. This higher bar is designed to detect outliers and structural flaws where a TSS is misplaced. Finally, the 40% (R-1) and 10% (R-2) share thresholds are design parameters to ensure a balanced and viable network, preventing bottlenecks and the inclusion of under-utilized sites.

R-3: Network Coverage

This requirement ensures that the Hub-and-Spoke system functions as intended, with the vast majority of material flowing through the designed network. It measures the percentage of total generated tonnage that is routed via a TSS. The network coverage is considered insufficient if this value falls below 90%. The formula to calculate it is:

$$\text{Coverage} = \frac{\sum_{\text{all hubs+spokes}} \text{Tonnes}}{\text{Total tonnes generated}} \tag{3.4}$$

3.7.2. Qualitative Evaluation

The second phase of evaluation takes the quantitatively refined artifact (Artifact V2) and assesses its practical feasibility and strategic alignment with real-world conditions. This is achieved through a qualitative methodology centered on a series of semi-structured interviews with experts. This method was chosen to gather in-depth, contextual knowledge that cannot be captured through spatial data alone and to stress-test the model's assumptions against the tacit knowledge of experienced practitioners.

The interviews were guided by a core set of thematic questions to ensure consistency while allowing for emergent themes. With consent, the interviews were summarized, and the data was analyzed using a thematic analysis approach, with key insights coded according to the core themes of the research (e.g., spatial scale, operational complexity, governance). Experts were selected through purposive sampling to provide a comprehensive view of the problem, covering strategic, municipal, practical, and academic perspectives. The selected panel of experts includes:

- A strategic expert on circularity and policy with close ties to the municipality (Expert 1 or E1).
- A senior advisor on sustainable urban development within the City of Amsterdam (Expert 2 or E2).
- An academic researcher with expertise in circular hub optimization and logistics modeling (Expert 3 or E3).
- An experienced road maintenance contractor with direct, on-the-ground operational knowledge (Expert 4 or E4).

The feedback gathered from this expert evaluation serves as a crucial input for the final conceptual refinement of the network design, as will be detailed in the Discussion chapter. Full summaries of each interview are provided in Appendix C and D.

3.8. Activity 3: Re-Design

If the evaluation in Activity 5 reveals that a configuration is unsatisfactory, the DSRM process enters an iterative redesign loop. This approach is based on the understanding that early model runs often reveal unexpected inefficiencies or spatial imbalances that can be addressed through targeted adjustments. A key part of the refinement method involves a diagnostic review of the initial simulation results to identify specific performance issues. These issues include significant imbalances in material throughput among CCHs, the identification of specific TSS locations that contribute excessively to system tonne-kilometers due to inefficient routing, or geographical zones that are clearly underserved by the initial network.

Based on this diagnostic review, two main adjustment methods were designed. First, a CCH Network Expansion method was developed to address workload imbalances and geographical service gaps. This process involves activating additional CCHs from the pool of suitable candidates identified during the initial design phase. These sites are selected strategically to improve service coverage and better distribute logistical pressure across the network.

Second, a method was designed for TSS Network Optimization within the Hub-and-Spoke model. This involves pruning inefficient TSS locations and applying a Greedy Heuristic algorithm to select an enhanced set of sites. This algorithm uses an Iterative Best Addition strategy to evaluate potential TSS additions based on a hierarchy of performance criteria:

1. maximizing the total tonnage captured by the TSS network,
2. minimizing the onward TSS-to-CCH distance for consolidated loads, and
3. minimizing the overall system tonne-kilometers.

The detailed methodology of this Greedy Heuristic is provided in Appendix B.

Once these refinement methods are applied, the resulting redesigned network configuration is then re-demonstrated (Activity 4) and re-evaluated (Activity 5) to measure the impact of the improvements.

3.9. Activity 6: Communication

The final activity in the DSRM process is to communicate the research findings to relevant stakeholders. The primary medium for this communication is this thesis itself. This document serves as the comprehensive and formal report of the entire research journey. It documents the problem, the design and development of the initial and refined artifacts, and the iterative quantitative and qualitative evaluation processes. By presenting the full DSRM cycle, from problem identification to the final conceptual blueprint, this thesis fulfills its role as the primary communication artifact of the research project.

4

Result and Analysis

4.1. Overview

This chapter presents the quantitative results from applying the Design Science Research Methodology (DSRM) described in Chapter 3. The findings are structured according to the iterative steps of the DSRM process, ensuring a clear and logical progression that reflects the research approach.

The chapter starts with the results of the Initial Design (Activity 3), outlining the proposed locations for Circular Construction Hubs (CCHs) and Temporary Storage Sites (TSSs) that form the basis of the initial artifact. It then details the first DSRM iteration, presenting the outcomes of the Initial Demonstration (Activity 4) and the subsequent Initial Evaluation (Activity 5). This evaluation identifies key performance issues in the initial design and provides evidence for further refinement.

Next, the chapter reports on the Redesign phase (Activity 3, Loop), which introduces an expanded CCH network and an optimized TSS network developed using algorithmic methods. These changes result in the refined artifact.

The chapter then covers the final iteration, including the Re-demonstration (Activity 4, Loop) and the Final Re-evaluation (Activity 5, Loop). This leads to a comparative analysis of all refined configurations, assessing their efficiency and operational characteristics. The chapter concludes with a summary of the main findings from the entire analysis.

4.2. Activity 3: Initial Design

The first step in the DSRM process was the initial design of the artifact's core components: a set of candidate locations for Circular Construction Hubs (CCHs) and Temporary Storage Sites (TSSs). The application of the GIS-based suitability and screening models, as described in previous chapter, resulted in a preliminary set of facilities to be used in the first modeling iteration.

The suitability analysis for main CCHs identified three primary industrial areas as the most promising candidate locations:

1. Havens-West, Westpoort, West
2. Noordelijke IJ-oevers-West, Oud-Noord
3. Omval/Overamstel, Watergraafsmeer, Oost

Complementing these main hubs, the strategic screening process for smaller, intermediate consolidation points identified eight potential TSS locations distributed across the city:

1. Amstel III/Bullewijk
2. De Punt
3. Middenmeer

4. Nellestein
5. Noordelijke IJ-oevers-Oost
6. Oostelijk Havengebied
7. Rijnbuurt
8. Westlandgracht

The spatial distribution of this initial set of three CCHs (represented by star symbols) and eight TSSs (represented by hexagon symbols) is illustrated in Figure 4.1. This network of eleven potential sites formed the foundational input for the first demonstration and evaluation of the network configuration models.

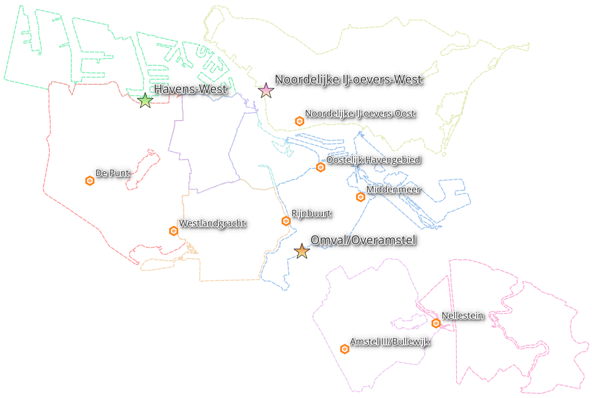


Figure 4.1: Spatial distribution of initial candidate CCH and TSS locations.

The characteristics and performance of networks built using these initial CCH and TSS locations are detailed in the following section.

4.3. Activity 4: Initial Demonstration

The initial artifact, consisting of 3 CCH and 8 TSS locations, was demonstrated by applying the three network configuration models to the Amsterdam case data. This demonstration generated the baseline performance data for each logistical strategy.

4.3.1. Centralized

The Centralized configuration assumed all road maintenance materials were transported to a single CCH. Preliminary analysis of total travel distances from all material sources to each of the three primary CCH candidates (Omval/Overamstel, Havens-West, and Noordelijke IJ-oevers West) indicated that designating Omval/Overamstel as the sole hub resulted in the lowest cumulative travel distance.

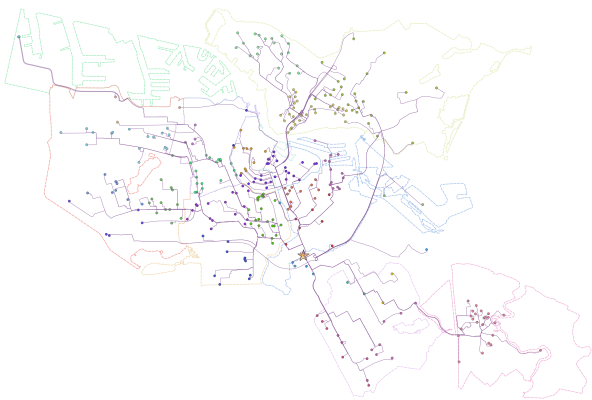


Figure 4.2: Material flow allocation in Centralized configuration.

Table 4.1 summarizes the trip distance statistics and resulting tonne-kilometers when each of the three primary CCH candidates were considered as a single central hub. For the Omval/Overamstel Centralized scenario, the total tonne-kilometers was calculated at **1,702,150 t-km**, total travel distance of **1,725 km** with an average of **5.48 km** per material source trip.

Table 4.1: Centralized configuration statistics

Location	Total Distance (km)	Mean Distance (km)	Total Tonnage (t)	Total Tonne-km (t-km)
Omval/Overamstel	**1,725**	**5.48**	324,947	**1,702,150**
Havens-West	2,278	7.23	324,947	2,532,130
Noordelijke W.	2,037	6.47	324,947	1,922,070

The data presented in Table 4.1 highlights the significant tonne-kilometersburden associated with consolidating all materials at a single point, particularly if a less optimally located CCH were chosen. The performance of the Omval/Overamstel Centralized configuration serves as a baseline for comparison against the more distributed network configurations.

4.3.2. Decentralized

The initial decentralized configuration distributed the logistical load across the three primary CCH candidate locations: Havens-West, Noordelijke IJ-oevers West, and Omval/Overamstel. Materials from each source point were routed to the geographically nearest of these three CCHs.

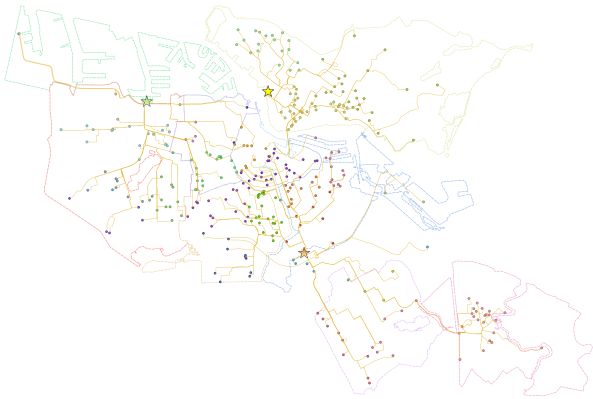


Figure 4.3: Material flow allocation in the initial 3-CCH decentralized configuration.

The performance statistics for this all CCH in decentralized network are detailed in Table 4.2. This configuration resulted in a total system distance of **1,575.72 km** and system tonne-kilometers of **1,580,070 t-km**. As shown, the distribution of workload among the three CCHs was notably uneven as Omval/Overamstel handled the largest share, processing 174,383 tonnes from 157 projects and accounting for 964,805 t-km. In contrast, Havens-West handled 65,223 tonnes (78 projects, 306,890 t-km) and Noordelijke IJ-oevers West handled 85,341 tonnes (80 projects, 308,375 t-km).

Table 4.2: Statistics of decentralized configuration.

Location	Total Distance (km)	Mean Distance (km)	Projects Served (#)	Total Tonnage (t)	Total Tonne-km (t-km)
Havens–West	372.81	4.78	78	65,223	306,890
Noordelijke W.	325.24	4.07	80	85,341	308,375
Omval/Overamstel	877.66	5.59	157	174,383	964,805
Totals	**1,575.72**	–	315	324,947	**1,580,070**

The previous table shows how distributing the CCHs would affect travel distances and workload distributions compared to a fully-Centralized approach.

4.3.3. Hub-and-Spoke

The initial Hub-and-Spoke configuration utilized the same three primary CCHs as the initial decentralized configuration and incorporated the eight TSS locations. A hybrid routing logic was employed: materials were directed from their source to the nearest active TSS only if the network distance to that TSS was shorter than the direct network distance to the nearest active CCH; otherwise, materials flowed directly from the source to the nearest active CCH. Materials consolidated at a TSS were then transported via a second leg to the nearest active CCH.

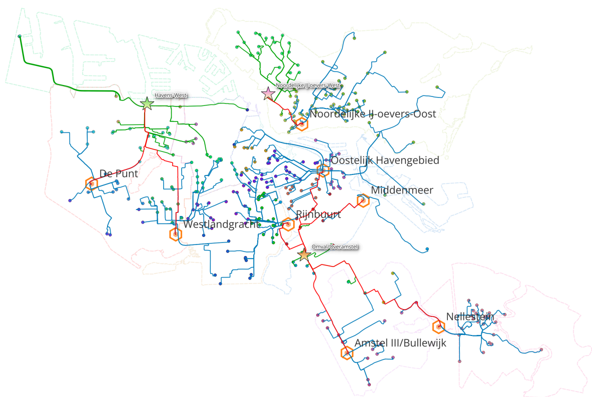


Figure 4.4: Material flow allocation in Hub-and-Spoke configuration, color coded in red (TSS to CCH), blue (projects to TSS), and green (projects to CCH).

The simulation involved determining the appropriate first leg for each material source and subsequently calculating the weighted second leg for materials transiting through a TSS. Table 4.3 presents the statistics for materials that were routed directly to one of the three CCHs and Table 4.4 provides a performance breakdown for each of the eight active TSS locations.

Table 4.3: Hub-and-Spoke model - statistics for CCH (direct)

Location	Total Distance (km)	Mean Distance (km)	Projects Served (#)	Total Tonnage (t)	Total Tonne-km (t-km)
Omval/	12.14	1.73	7	8,872	13,027
Havens-West	75.59	3.15	24	14,591	40,592
Noordelijke W.	74.76	3.11	24	23,138	52,690
Totals	**162.49**	**–**	**55**	**46,601**	**106,310**

Table 4.4: Hub-and-Spoke model - statistics for TSS

Location	Projects Served (#)	Total Tonnage (t)	Total Leg 1 (km)	Total Leg 2 (km)	Total Leg 1 (t-km)	Total Leg 2 (t-km)
Amstel III/B.	15	37,104	28.18	73.12	114,029	180,874
De Punt	15	16,847	32.30	79.54	31,867	88,454
Middenmeer	2	9,547	7.63	10.21	24,372	48,747
Nellestein	26	23,001	84.06	240.50	75,496	205,950
Noordelijke O.	48	57,248	112.37	110.63	121,544	131,948
Oostelijk H.	63	41,256	164.49	309.67	102,466	199,620
Rijnbuurt	46	42,365	112.12	139.05	89,280	120,219
Westlandgracht	38	50,978	111.83	290.56	137,375	357,658
Totals	**253**	**278,346**	**649.19**	**1,207.50**	**696,430**	**1,333,472**

Under this initial configuration, 55 projects, accounting for 46,601 tonnes of material, were transported directly to CCHs. These direct flows contributed 106,310 t-km over a total travel distance of 159.38 km. In total, 253 projects, representing 278,346 tonnes of material, were routed via these intermediate consolidation sites. The combined Leg 1 (Origin-to-TSS) tonne-kilometers for these materials involved a total travel distance of 649.19 km, resulting in a tonne-kilometers of 696,430 t-km. The subsequent weighted Leg 2 (TSS-to-CCH) tonne-kilometers, accounting for the onward journey of consolidated materials to the nearest CCH, amounted to 1,333,472 t-km. Consequently, the total system tonne-kilometers for this initial configuration was **2,136,211 t-km** and total distance covered of **2,019.18 km**.

The data presented in previous tables provide a quantitative overview of the material flows and tonne-kilometers within this initial configuration, detailing the contributions of both direct-to-CCH movements and the two-stage movements via TSS. These performance characteristics subsequently informed the iterative refinement process detailed in the following stages.

4.4. Activity 5: Initial Evaluation

Following the demonstration of the initial models, a formal evaluation was conducted against the requirements established in previous chapter. The analysis confirmed that the initial artifact was unsatisfactory, with the Decentralized model failing the hub balance requirement and the Hub-and-Spoke model failing requirements for both spoke efficiency and system coverage

This configuration failed requirement R-1 (Hub Balance), which states that no single hub should handle more than 40% of the system's tonne-kilometers. Table 4.5 provides a summary of the workload distribution to confirm the failure.

Table 4.5: R-1 evaluation for CCH

CCH Location	Tonne-km (t-km)	Share of Total t-km (%)	Verdict
Havens-West	306,890	19.40%	Pass
Noordelijke W.	308,375	19.50%	Pass
Omval/Overamstel	964,805	61.10%	FAIL

As shown in the table, the Omval/Overamstel hub handles 61.10% of the total transport effort, significantly exceeding the 40% threshold. This indicates a severe workload imbalance and major geographical service gaps, justifying the redesign action of expanding the CCH network.

This workload imbalance is driven by the spatial distribution of upcoming road maintenance. As the heatmap in Figure 4.5 illustrates, there are high concentrations of projected tonnage in districts not optimally serviced by the initial 3-CCH network. This indicates major geographical service gaps and justifies the redesign action of expanding the CCH network.

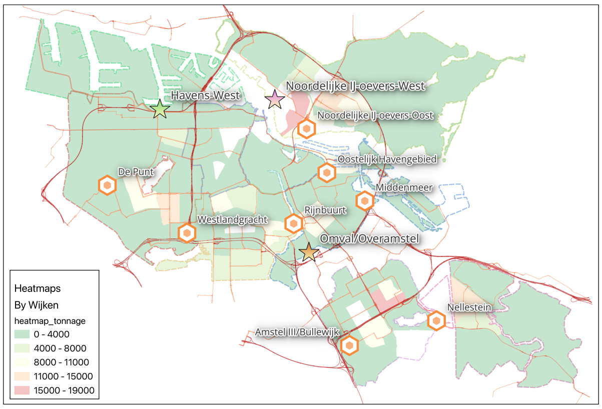


Figure 4.5: Heatmap of projected tonnage by *wijken*.

Moreover, the initial configuration also failed to satisfy R-2 (Spoke Efficiency), which states that the network is unsatisfactory if any single TSS fails all three efficiency sub-tests. Table 4.6 provides the detailed performance analysis for each of the eight initial TSS locations.

Table 4.6: R-2 evaluation for TSS

TSS Location	km/t (>6)	km/project (>8)	tonne-share (<10%)	Verdict
Oostelijk H.	7.32	7.53	14.8%	Pass
Westlandgracht	9.71	10.59	18.3%	Pass
Nellestein	12.24	12.48	8.3%	FAIL
De Punt	7.14	7.46	6.1%	Pass
Rijnbuurt	5.00	5.46	15.2%	Pass
Noordelijke O.	4.43	4.65	20.6%	Pass
Amstel III/B.	7.95	6.75	13.3%	Pass
Middenmeer	7.66	8.92	3.4%	FAIL

Finally, the initial Hub-and-Spoke model failed Requirement R-3 (Network Coverage). The analysis showed that only 85.60% (278,346 tonnes out of a total 324,947 tonnes) was consolidated through the TSS network, falling of the 90% threshold. This indicates the initial TSS locations were not optimally placed to serve as the primary consolidation pathway.

Overall, the initial artifact failed to meet the established performance requirements for Hub Balance (R-1), Spoke Efficiency (R-2), and Network Coverage (R-3). This evaluation provides the direct justification for triggering the 'No - Refine' path in the DSRM flowchart and applying the redesign methods detailed in the next section.

4.5. Activity 3: Re-Design

The initial evaluation concluded that the initial network configurations were unsatisfactory, triggering the iterative redesign loop. This section presents the results of applying the refinement methods to address the identified performance issues, aiming to improve geographic coverage, balance workloads, and enhance overall logistical efficiency.

4.5.1. Expansion of the CCH Network

The redesign process began by addressing the failure of Requirement R-1 (Hub Balance). The initial evaluation concluded that this configuration was unsatisfactory due to a significant concentration of workload at the Omval/Overamstel hub, which handled over 60% of the system's tonne-kilometers.

This imbalance was primarily the result of a mismatch between the initial hub locations and the spatial distribution of projected road maintenance tonnage. High-density clusters of activity were concentrated in the Zuid, Oost, and southeastern Zuidoost districts, while the existing hubs did not adequately serve these areas. Analysis of Figure 4.5 further revealed service gaps in the southern and western parts of Amsterdam, where substantial volumes of material were not efficiently routed. To address these issues, more suitable CCH sites are needed in order to improve service coverage and reduce inefficiencies in the network. New CCH sites were selected based on two key criteria: areas with a high concentration of logistical activity (measured in tonnage and number of projects)and locations with significant second-leg transport inefficiencies. Promoting these areas to CCH status targeted the most significant sources of network inefficiency, aiming to balance hub workloads and lower total tonne-kilometers.

As a result, two additional candidate CCH locations were activated from the pool identified in the initial design phase. These new sites were chosen to close the identified service gaps and address the flaws highlighted by the initial evaluation.

While other sites were considered, an analysis confirmed the optimal choices. For instance, Oostelijk Havengebied was dismissed due to its predominantly residential zoning, and Amstel III/Bullewijk, while close, did not solve the problem of long-haul routes. Therefore, the following locations were selected for expansion:

1. **Westlandgracht (Candidate #1):** this area was identified as a high-volume logistical hotspot with a highly inefficient second-leg journey in the initial Hub-and-Spoke model. Its selection addresses the service gap in the west, and its suitability is reinforced by its industrial zoning.
2. **Nellestein (Candidate #2):** Located in the southeastern Zuidoost area, this site was proposed to directly serve a substantial volume of projected materials. Its selection could solves the most significant long-haul inefficiency identified in the initial network.

The locations of these two proposed CCH sites are visualized in Figure 4.6, which shows their positions relative to projected road maintenance demand, industrial zones, and the original CCH network. This map highlights how the selected sites address both the identified service gaps and the logistical needs of the network.

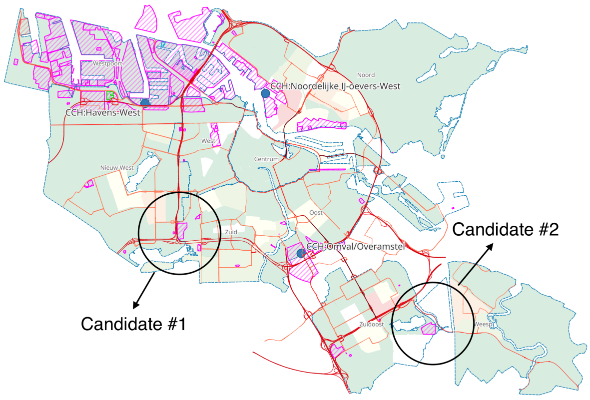


Figure 4.6: Proposed locations shown in relation to projected road maintenance tonnage (heatmap), industrial areas (purple highlights), and initial CCH locations (blue node).

The activation of these two additional CCHs resulted in a refined 5-CCH network (Havens-West, Noordelijke IJ-oevers-West, Omval/Overamstel, Westlandgracht, and Nellestein), as shown in Figure 4.7. This expanded network formed the basis for the refined model evaluations.

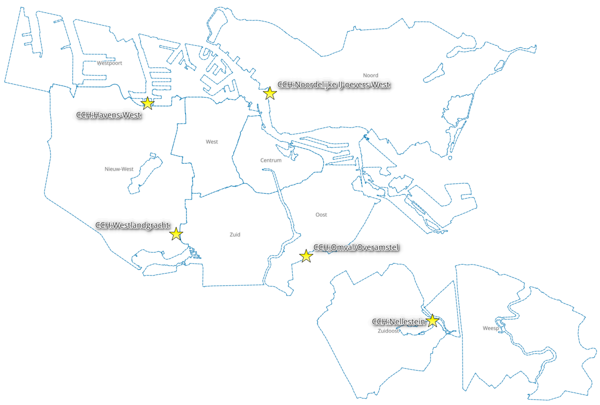


Figure 4.7: Spatial layout of the refined 5-CCH network.

This expanded network formed the basis for the refined Decentralized model and the refined Hub-and-Spoke model evaluations.

4.5.2. Adjustment of TSS Network

The second redesign action addressed the failure of the initial Hub-and-Spoke model to meet both Requirement R-2 (Spoke efficiency) and Requirement R-3 (Network Coverage). The initial evaluation showed that the network contained inefficient nodes and that the TSS network was not serving as the primary consolidation pathway. This justified a complete redesign of the TSS network.

To determine an improved number and configuration of TSSs to operate in conjunction with the refined 5-CCH network, the Greedy Heuristic algorithm was employed. The detailed methodology of this algorithm is provided in Appendix B. The algorithm was run to iteratively add up to 20 potential TSSs, with the performance at each stage is summarized in Table 4.7 (see Table B.1 for full table) and visualized in Figure 4.9.

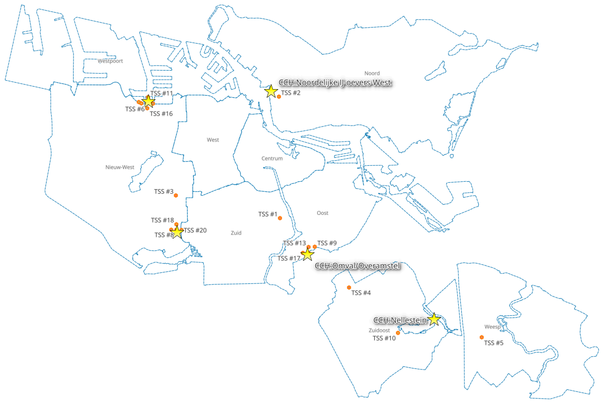
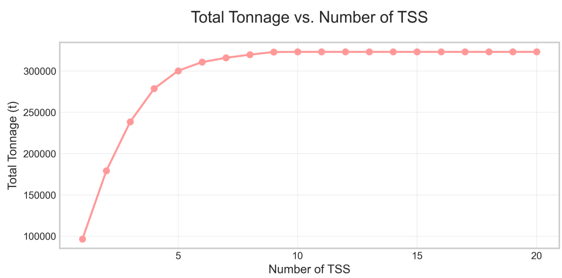


Figure 4.8: Spatial distribution of the refined 5-CCH network and the 20 algorithmically selected TSS.

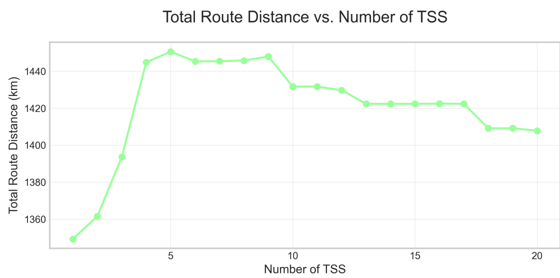
Table 4.7: Greedy Algorithm results for TSS locations (snapshot).

TSS Amount (#)	Projects Served (#)	Total Tonnage (t)	Δ Tonnage (%)	Total Distance (km)	Δ Distance (%)	Total Tonne-km (t-km)	Δ Tonne-km (%)
0	0	0	-	1,232.72	-	1,143,407	-
5	269	300,244	+7.77	1,450.58	+0.40	1,484,711	+0.26
10	305	323,124	+0.06	1,431.68	-1.12	1,431,259	-3.55
20	305	323,124	+0.00	1,407.81	-0.09	1,384,433	-0.20

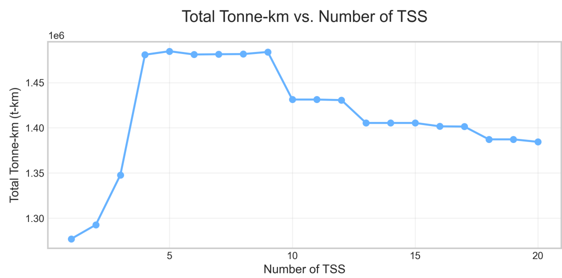
Figure 4.9a illustrates that total tonnage captured by the TSS network rises with the initial additions, reaching its maximum attainable level of approximately 323,124 tonnes by the 10th TSS; no further significant material volume is captured by adding TSS beyond this point. Simultaneously, Figure 4.9b and 4.9c show that total system tonne-kilometers and distance kilometers initially increase, peaking around the 5th TSS, and then exhibit a downward trend as additional TSS are inserted.



(a) Total tonnage vs. number of TSS.



(b) Total distance vs. number of TSS.



(c) Total tonne-km vs. number of TSS.

Figure 4.9: Iterative performance metrics of greedy heuristic for TSS selection.

Based on these results, specifically achieving full material tonnage capture (Figure 4.9a) while also reducing total tonne-kilometers and route distance from their earlier peaks (Figures 4.9b and 4.9c), the 10-TSS configuration was identified as a well-balanced outcome. Moving from five to ten TSS captures all remaining available tonnage while eliminating approximately 53,000 t-km and 19 km compared to the 5-TSS peak-effort configuration. While further marginal reductions in t-km and distance are observed by extending to 20 TSS, these come with no additional tonnage capture. The spatial distribution of these ten algorithmically selected TSS in relation to the 5-CCH network is illustrated in Figure 4.10.

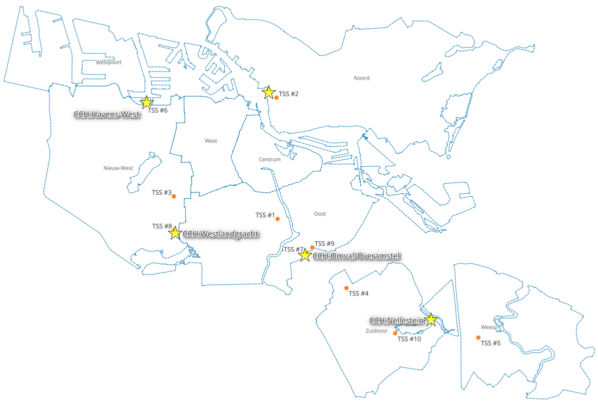


Figure 4.10: Spatial distribution of the 5-CCH and 10-TSS for the refined configurations.

Therefore, the set of ten TSS locations selected by the algorithm at this process was chosen for the refined Hub-and-Spoke model. This finding, which identifies a clear "elbow point" of diminishing returns around the 10-TSS mark, was highlighted during expert consultations as a particularly insightful and valuable result for municipal decision-makers, as it demonstrates that substantial network efficiency can be achieved with a relatively small number of strategically placed hubs (Expert 3, Appendix C.3).

4.6. Activity 4: Re-Demonstration

After the redesign process resulted a refined set of 5 CCHs and an optimized set of TSSs, the final iteration of the DSRM cycle was done. This section presents the results of re-demonstrating the network configurations with the improved artifact and provides a final evaluation and comparative analysis.

4.6.1. Centralized

The Centralized model, serving as a consistent baseline, continued to utilize the Omval/Overamstel CCH as the single destination point for all road maintenance materials. Table 4.8 presents the statistics for this refined Centralized configuration, which also includes a re-evaluation of other potential single CCH locations (Havens-West, Noordelijke W., Nellestein, and Westlandgracht) for comparative context.

Table 4.8: Statistics of refined Centralized configuration.

CCH Location	Total Distance (km)	Mean Distance (km)	Total Tonnage (t)	Total Tonne-km (t-km)
Omval/Overamstel	**1,725**	**5.48**	324,947	**1,702,150**
Havens-West	2,278	7.23	324,947	2,532,130
Noordelijke W.	2,037	6.47	324,947	1,922,070
Nellestein	3,785	12.29	324,947	3,729,056
Westlandgracht	2,684	8.71	324,947	2,867,498

As shown in Table 4.8, when Omval/Overamstel serves as the sole CCH, the total system tonne-kilometers remains at 1,702,150 t-km, with an average travel distance of 5.48 km per material source trip, handling the total system tonnage of 324,947 tonnes. The table also illustrates that if any of the other four CCHs were used as the single Centralized hub, the total tonne-kilometers would be significantly higher, reaffirming Omval/Overamstel's relative advantage as a singular consolidation point within this specific dataset.

4.6.2. Decentralized

The refined Decentralized model incorporated the expanded network of five CCHs: Havens-West, Nellestein, Noordelijke IJ-oevers West, Omval/Overamstel, and Westlandgracht. Figure 4.11 illustrates material flow allocation using this refined configuration.

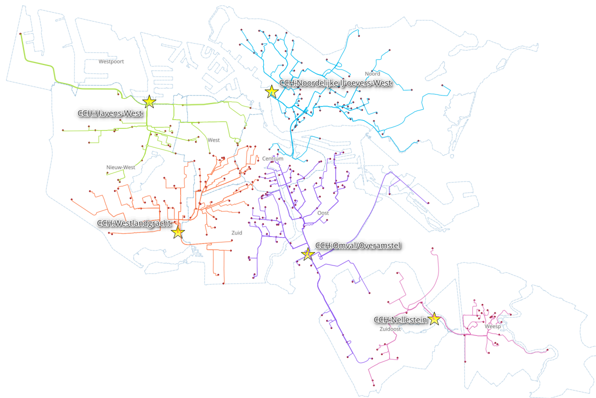


Figure 4.11: Material flow allocation in the refined 5-CCH decentralized configuration.

Table 4.9 details the performance statistics for this 5-CCH refined decentralized network. This configuration achieved a total system tonne-kilometer seffort of 1,166,416 t-km, with a total network distance of 1,232.72 km.

Table 4.9: Statistics of refined Decentralized configuration.

CCH Location	Total Distance (km)	Mean Distance (km)	Projects Served (#)	Total Tonnage (t)	Total Tonne-km (t-km)
Havens–West	122.88	3.61	34	27,663	99,488
Nellestein	144.44	4.13	35	59,376	227,911
Noordelijke W.	325.24	4.07	80	85,341	308,376
Omval/Overamstel	386.71	3.99	97	85,928	321,361
Westlandgracht	253.45	3.67	69	66,639	209,281
Totals	**1,232.72**	–	315	324,947	**1,166,416**

Analysis of the workload distribution in Table 4.9 shows how the five CCHs shared the logistical load. Overall, it could be inferred that the addition of two new CCHs leads to more balanced workload and shorter average travel distances to CCHs compared to the initial 3-CCH decentralized model. This configuration resulted in a total system distance of **1,232.72 km** and system tonne-kilometers of **1,166,416 t-km**.

4.6.3. Hub-and-Spoke

The refined Hub-and-Spoke model was developed to leverage the expanded 5-CCH network and incorporated a strategically selected set of ten TSS. Figure 4.12 illustrates the material flows within this refined configuration, showing direct project-to-CCH flows as well as the two-leg project-to-TSS and TSS-to-CCH movements.

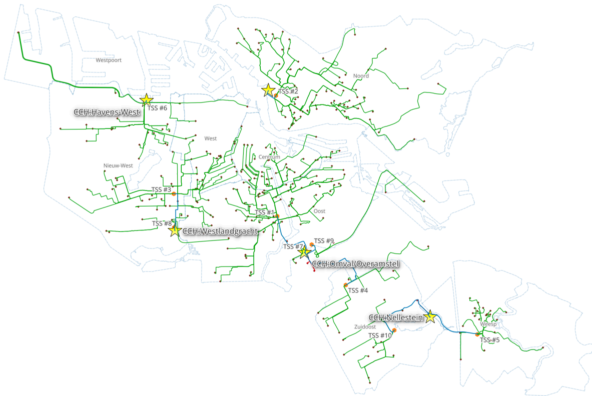


Figure 4.12: Material flow allocation in the refined 5-CCH and 10-TSS Hub-and-Spoke configuration.

Table 4.10 presents the statistics for materials that were routed directly to one of the five CCHs. A very small portion of the total material flow, only 3 projects accounting for 1,823 tonnes, took this direct path. These direct flows contributed 1,162.04 t-km over a combined travel distance of only 2.54 km, primarily involving material sources very close to the Omval/Overamstel and Nellestein CCHs.

Table 4.10: Refined Hub-and-Spoke model - statistics for CCH (direct)

CCH Location	Projects Served (#)	Total Tonnage (t)	Total Distance (km)	Total Tonne-km (t-km)
Nellestein	1	4	1.03	4
Omval/Overamstel	2	1,819	1.51	1,158
Totals	**3**	**1,823**	**2.54**	**1,162**

The majority of the material was routed via the ten active TSS, as detailed in Table 4.11. In total, 305 projects, representing 323,124 tonnes of material, were consolidated through these TSS locations. The combined Leg 1 (Origin-to-TSS) tonne-kilometers for these materials involved a total travel distance of 845.49 km, resulting in a tonne-kilometers of 810,262 t-km. The subsequent weighted Leg 2 (TSS-to-CCH) tonne-kilometers, accounting for the onward journey of consolidated materials from these ten TSS to their nearest of the five CCHs, amounted to 618,794 t-km. The sum of the unweighted Leg 2 path distances from each TSS to its designated CCH was 544.25 km.

Table 4.11: Refined Hub-and-Spoke model – statistics for TSS

TSS Location	Projects Served (#)	Total Tonnage (t)	Total Leg 1 (km)	Total Leg 2 (km)	Total Leg 1 (t-km)	Total Leg 2 (t-km)
#1 IJselbuurt	101	93,185	268.39	270.68	242,410	249,736
#2 Noordelijke W.	76	82,567	260.78	39.52	250,073	42,935
#3 Westlandgracht (a)	49	60,855	125.14	92.61	137,048	115,016
#4 Amsterdamse Poort e.o.	8	4,181	20.38	31.12	10,806	16,264
#5 Aetsveld/Oostelijke V.	23	21,639	35.30	63.71	32,781	59,940
#6 Havens-West	25	12,484	77.62	3.00	30,029	1,498
#7 Omval/Overamstel (a)	2	5,187	2.17	0.24	5,499	622
#8 Westlandgracht (b)	7	3,829	15.45	1.12	7,302	613
#9 Omval/Overamstel (b)	3	3,201	17.20	2.76	24,241	2,945
#10 Nellestein	11	35,996	23.06	39.49	70,075	129,226
Totals	**305**	**323,124**	**845.49**	**544.25**	**810,262**	**618,794**

Note: *this table reports the final tonnage served once all 10 TSS are active under the full hub-and-spoke assignment. However, the greedy algorithm actually selected each site based on its marginal tonnage at the time of insertion. For the per-step* Δ *tonnage values, see Table B.1 in the Appendix B.*

The total system tonne-kilometers for this refined Hub-and-Spoke configuration was **1,430,218 t-km** and the total distance covered (using compounded calculation) amounted to **1,393.27 km**.

It could be seen that the material throughput for each of the ten active TSS sites within this configuration revealed that a subset of these sites is inefficient (TSS #4, #7, #8, #9). They demonstrated lower tonnage capture compared to the other active TSS once the full network of ten was operational. This observation prompted an investigation into whether a more streamlined Hub-and-Spoke network, with fewer TSS, could maintain comprehensive material capture while potentially further reducing system tonne-kilometers and network distance, thereby improving overall efficiency and reducing the operational footprint. Consequently, these identified low-throughput TSS were systematically removed from the candidate set.

Table 4.12 summarizes the material flow allocation and logistical performance for direct-to-CCH deliveries within this 6-TSS Hub-and-Spoke configuration, while Table 4.13 details the statistics for materials routed via the six active TSS.

Table 4.12: Refined and adjusted Hub-and-Spoke model - statistics for CCH (direct)

CCH Location	Projects Served (#)	Total Tonnage (t)	Total Distance (km)	Total Tonne-km (t-km)
Havens-West	3	947	9.11	2,130
Nellestein	3	1,852	10.17	8,110
Omval/Overamstel	10	11,185	32.23	35,761
Westlandgracht	6	3,749	12.38	7,234
Totals	**22**	**17,733**	**63.89**	**53,235**

In this refined 6-TSS configuration, 22 projects, accounting for 17,733 tonnes of material, were transported directly to one of the five CCHs. This typically occurs when the material source is in very close proximity to a CCH, making a direct trip more efficient than a two-leg journey via a TSS. These direct deliveries contributed 53,235.58 t-km to the total system effort, with an average direct haul distance of 2.90 km.

Table 4.13: Refined and adjusted Hub-and-Spoke model – statistics for TSS

TSS Location	Projects Served (#)	Total Tonnage (t)	Total Leg 1 (km)	Total Leg 2 (km)	Total Leg 1 (t-km)	Total Leg 2 (t-km)
#1 IJselbuurt	103	93,625	275.14	274.30	242,898	249,329
#2 Noordelijke W.	76	82,567	260.99	39.70	250,097	43,134
#3 Westlandgracht (a)	48	60,495	122.64	93.22	136,149	117,482
#5 Aetsveld/Oostelijke V.	23	21,639	35.34	63.81	32,821	60,034
#6 Havens-West	22	11,537	68.27	1.07	27.848	562.96
#10 Nellestein	14	37,531	32.82	50.33	74.862	129,226
Totals	**286**	**307,124**	**795.20**	**522.43**	**764,676**	**604,818**

Collectively, the six active TSS processed 307,214 tonnes of material from 286 projects (94.54% of total tonnage captured). The first leg of transport (from project sites to these TSS) amounted to 764,676.46 t-km, with an average haul distance to a TSS of 2.78 km. The subsequent onward journey (Leg 2, from TSS to the nearest CCH) contributed 604,018.52 t-km, with a notably short average TSS-to-CCH distance of 1.83 km, reflecting the efficiency gained from the CCH network expansion and TSS pruning. This two-stage process via TSS resulted in a combined total distance of **1,381.52 km** and system tonne-kilometers of **1,422,729 t-km**.

4.7. Activity 5: Re-Evaluation

The next activity in the DSRM evaluation loop is the re-evaluation of the refined artifact. This involves a formal assessment of the refined network configurations against the requirements defined in previous chapter, a direct comparative analysis to quantify the impact of the iterative redesign process, and a final comparison to determine the most suitable network model.

4.7.1. Requirements Check

To formally validate the success of the redesign process, the refined Decentralized and Hub-and-Spoke models were re-evaluated against the same network design requirements (R-1, R-2, and R-3) they previously failed.

The refined 5-CCH Decentralized model was tested against the R-1 requirement, which stipulates that no single hub should handle more than 40% of the total system tonne-kilometers. The workload distribution, is shown in Table 4.14.

Table 4.14: R-1 evaluation for CCH

CCH Location	Tonne-km (t-km)	Share of Total t-km (%)	Verdict
Havens-West	99,488	8.50%	Pass
Nellestein	227,911	19.50%	Pass
Noordelijke W.	308,376	26.40%	Pass
Omval/Overamstel	321,361	27.60%	Pass
Westlandgracht	209,281	18.00%	Pass

As the analysis confirms, the workload is now significantly more balanced. The busiest hub, Omval/Overamstel, handles only 27.60% of the total transport effort, well below the 40% threshold. Therefore, the refined Decentralized configuration successfully passes requirement R-1.

Then, the Hub-and-Spoke network was tested against the R-2 (Spokes Efficiency) requirement. The efficiency for spokes is shown in Table 4.15.

Table 4.15: R-2 evaluation for TSS

TSS Location	km/t (>6)	km/project (>8)	tonne-share (<10%)	Verdict
#1 Ijselbuurt	5.87	5.33	28.80%	Pass
#2 Noordelijke W.	3.64	3.96	25.40%	Pass
#3 Westlandgracht (a)	3.57	4.40	18.60%	Pass
#5 Aetsveld/Oostelijke V.	4.58	4.29	6.70%	Pass
#6 Havens-West	5.97	3.15	3.60%	Pass
#10 Nellestein	4.34	4.81	11.60%	Pass

The evaluation demonstrates that none of the active TSS in the refined configuration fails all three subtests simultaneously. The network pruning and strategic selection of TSS locations have successfully eliminated the inefficient nodes identified in the initial model. Therefore, the refined Hub-and-Spoke configuration passes requirement R-2.

Finally, for R-3 (Network Coverage), the analysis shows that the six active TSS processed 307,124 tonnes of material out of a total system tonnage of 324,947 tonnes. This results in a network coverage of 94.5%, which is above the 90% threshold. The model successfully passes requirement R-3.

4.7.2. Initial and Refined

The implemented refinements to the Decentralized and Hub-and-Spoke configurations yielded significant improvements in key performance metrics compared to their initial setups. Table 4.16 provides a side-by-side performance snapshot comparing the initial and refined versions of each network configuration based on total distance and tonne-kilometers.

Table 4.16: Comparison of initial and refined network configurations.

Configuration	Active facilities (initial → refined)	Initial Distance (km)	Refined Distance (km)	Δ Distance (%)	Initial Tonne-km (t-km)	Refined Tonne-km (t-km)	Δ Tonne-km (%)
Centralized	1C → 1C	1,725	1,725	0%	1,702,150	1,702,150	0%
Decentralized	3C → 5C	1,576	1,233	-22%	1,580,070	1,166,416	-26%
Hub-and-Spoke	3C8T → 5C6T	2,019	1,382	-32%	2,136,211	1,422,729	-33%

Centralized configuration remained unchanged, serving as a consistent baseline. It recorded 1,702,150 t-km and involved 1,725 total distance kilometers. While offering the shortest average trip distance (5.48 km per material source trip), its high system-wide t-km highlights the inherent cost of full centralization for a geographically dispersed demand.

For the Decentralized model, the network was expanded from three to five CCHs with the activation of Westlandgracht and Nellestein. This expansion was strategically implemented to address service gaps identified in the south-eastern and western parts of Amsterdam and to better balance the distribution of workload among facilities. This refinement resulted in a substantial 26% reduction in total tonne-kilometers (from 1,580,070 t-km to 1,166,416 t-km) and a 22% decrease in total distance kilometers (from 1,576 km to 1,233 km). Consequently, the distribution of workload across the CCHs became far more balanced; no single CCH handled more than approximately 28% of the total tonnage in the refined 5-CCH setup, a significant improvement from the initial 3-CCH configuration where the Omval/Overamstel CCH processed roughly 61% of the material.

Similarly, the Hub-and-Spoke system underwent significant refinement. The initial configuration (3 CCHs and 8 TSS) was expanded to 5 CCHs, and the TSS network was optimized through a two-stage process involving a greedy heuristic followed by analytical pruning, resulting in a final set of 6 strategically effective TSS (5C6T). Despite the inherent addition of tonne-kilometer legs associated with a two-stage system, this refined Hub-and-Spoke network demonstrated considerable improvement. It reduced total system tonne-kilometers by approximately 33% (from 2,136,211 t-km to 1,422,729 t-km) and physical route kilometers by roughly 32% (from 2,019 km to 1,382 km) compared to the initial 3-CCH, 8-TSS design. This efficiency gain was driven by several factors: the collection legs (Origin-to-TSS or direct-to-CCH) became significantly shorter than in the initial design, and the second-leg (TSS-to-CCH) tonne-kilometer burden was also notably reduced due to the more proximate and expanded CCH grid combined with a more optimally sized and located TSS network.

These comparative figures clearly demonstrate the substantial positive impact of the iterative and analytical refinement process on the overall logistical efficiency of the modeled networks. The detailed performance statistics for these final refined scenarios are presented in the following section.

4.7.3. Final Configurations

Having established the performance benefits of the refinement process, this section provides a direct comparison of the refined configurations: the Centralized model (1 CCH at Omval/Overamstel), the refined 5-CCH Decentralized model, and the refined 5-CCH, 6-TSS Hub-and-Spoke model. Table 4.17 summarizes their key performance indicators.

Table 4.17: Performance metrics for the refined network configurations

Configuration	Mean Distance (km)	Total Distance (km)	Total Tonne-km (t-km)
Centralized (1 CCH)	5.48	1,725	1,702,150
Decentralized (5 CCH)	3.91	1,233	1,166,416
Hub-and-Spoke (5 CCH + 6 TSS)	4.38	1,382	1,422,729

The refined Centralized model (1,702,150 t-km) remains a useful baseline but performs weakest on system-wide tonne-kilometers and total distance. Its single-hub simplicity could be considered if land-use, permitting, or capital constraints severely prohibit the establishment of multiple CCHs. However, from a circular economy and tonne-kilometers emissions perspective (as represented by t-km), it is the least favorable of the refined options.

The refined 5-CCH Decentralized model emerges as the overall efficiency winner based on the primary metrics. As shown in Table 4.17, it achieved the lowest total system tonne-kilometers (1,166,416 t-km), representing a 32% reduction compared to the Centralized model and a 22% reduction compared to the refined 6-TSS Hub-and-Spoke model. It also exhibited the shortest total network length (1,233 km) and the lowest mean distance per tonne of material moved (3.91 km). Furthermore, this configuration successfully addressed the workload imbalances of earlier iterations, with no single CCH handling more than approximately 28% of the total tonnage.

The refined 5-CCH, 6-TSS Hub-and-Spoke model, with 1,422,729 t-km, positions itself between the other two refined scenarios in terms of tonne-kilometers and total route kilometers (1,382 km). While its two-leg nature results in approximately 22% higher t-km than the refined Decentralized layout, it represents a significant improvement over its initial, less optimized version, successfully erasing most of the excess distance penalties observed in the initial 3-CCH, 8-TSS design. A key characteristic of this refined 6-TSS model is its high degree of material consolidation through its Temporary Storage Site (TSS) network, with approximately 94.5% of the total available material being routed via a TSS. This extensive utilization of the TSS network offers significant operational flexibility, particularly if CCH capacity is constrained, if direct access to CCHs is restricted for certain material sources, or if initial sorting/staging benefits are desired at intermediate locations. The reduction from ten to six TSS in the final refinement also points towards a more operationally streamlined network with a smaller physical footprint for temporary storage, while still achieving this high level of TSS-based material capture.

4.8. Concluding Evaluation

The study concludes that a decentralized network is the most transport-efficient configuration for Amsterdam's road maintenance logistics. The refined 5-CCH Decentralized model achieved the lowest total system tonne-kilometers (1,166,416 t-km), successfully addressing the workload imbalances of the initial design. As a strong alternative, the refined 6-TSS Hub-and-Spoke model demonstrates the value of a high-consolidation network (1,422,729 t-km) that offers significant operational flexibility.

Crucially, the iterative design and algorithmic optimization process identified the optimal strategic areas for these facilities. The final recommended network, combining the locations from the most successful models, is visualized in Figure

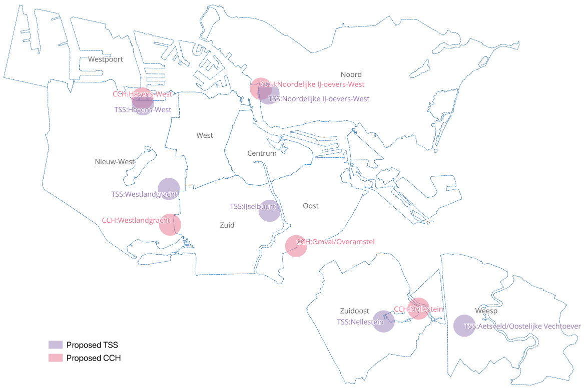


Figure 4.13: Proposed location of CCHs and TSSs in Amsterdam.

As illustrated, the final artifact proposes a network consisting of:

- **Five CCHs:**
  The analysis confirms that permanent hubs should be anchored in the industrial zones of Havens-West, Noordelijke IJ-oevers-West, Omval/Overamstel, Westlandgracht, and the high-tonnage area of Nellestein.
- **Six TSSs:**
  To support a flexible Hub-and-Spoke system, the analysis identified key locations for temporary sites, with highly effective nodes in areas such as IJselbuurt, Noordelijke W., and Aetsveld/Oostelijke Vechtoever.

The final recommended network, supported by both quantitative and spatial analysis, offers a clear and practical answer to the research questions. The next chapter will provide an in-depth discussion of these outcomes, examining their relevance to existing literature and exploring the practical challenges and opportunities for implementation in Amsterdam.

5 Discussion

5.1. Overview

This chapter transitions from the quantitative analysis presented in Chapter 4 to a broader interpretation of the findings, with the central purpose of answering the main research question: *"How could Circular Construction Hubs be strategically located and configured to support material reuse in urban road maintenance?"* The analysis of the refined network configurations in the previous chapter revealed a key strategic trade-off: the Decentralized network appears to be the most transport-efficient model, while the Hub-and-Spoke network offers greater operational flexibility and regulatory resilience at a measurable transport cost.

To delve deeper into the implications of these results, the chapter is structured to progressively address each of the sub-research questions. First, it interprets the performance of each network model to establish the fundamental principles of network design. Building on this, Section 5.3 synthesizes the findings from the iterative modeling process to derive a set of transferable principles for facility siting, directly addressing Sub-RQ1 on key location criteria.

Next, the chapter provides a two-part answer to Sub-RQ2, which concerns how to evaluate different configurations and their effectiveness. Section 5.2 begins this evaluation by interpreting the performance of the refined models to establish the core strategic trade-off. Section 5.4 then deepens this analysis by examining how the effectiveness of these models is impacted by the practical assumptions and real-world constraints of the Amsterdam context.

Subsequently, Section 5.5 synthesizes these findings to argue how a well-designed logistics network could overcome key economic and risk-related barriers, serving as the essential enabling mechanism for achieving high-value circularity. Finally, Section 5.7 concludes the discussion by distilling the key decision-making insights and methodological contributions that could support the planning of CCHs in other cities, thus providing a direct answer to Sub-RQ3 on transferable insights.

5.2. Interpreting Network Configuration

The quantitative results from Chapter 4 reveal that the spatial configuration of a hub network has a notable impact on its logistical performance. To understand the implications of these findings, this section interprets the three refined network models: Centralized, Decentralized, and Hub-and-Spoke. These specific configurations were chosen not as arbitrary theoretical constructs, but because they represent the primary network models that have emerged from both academic literature and practitioner discussions on circular logistics (Tsui et al., 2023). Analyzing the strengths and weaknesses of each reveals the fundamental principles of network design and establishes the fundamental strategic trade-off between transport efficiency and operational flexibility.

5.2.1. Centralized: A Baseline

The Centralized configuration, where a single CCH at Omval/Overamstel handled all road maintenance materials, served as the baseline for this study. This model represents the simplest network structure, but it resulted in the highest system tonne-kilometers (1,702,150 t-km) among all refined scenarios (Table 4.17). Although the average trip distance to the hub was relatively short (5.48 km, Table 4.8), this metric is misleading, as many material sources were located far from the hub, leading to long and inefficient haulage across the city.

The main drawback of a single centralized CCH in a city like Amsterdam is its inability to maintain proximity to all project sites, as emphasized by Nußholz et al. (2019). When all flows are routed through a single point, excessive transport could weakens environmental benefits, and poorly sited hubs could create inefficiencies such as double handling or detours. Centralized hubs may achieve economies of scale at high volumes (Shahparvari et al., 2020), but these benefits are only realized if demand is stable and concentrated.

Case studies such as the Brussels Construction Consolidation Center (BCCC) (Brusselaers & Mommens, 2022) and London Construction Consolidation Center (LCCC) (El Moussaoui et al., 2021) show that centralized hubs work best for large, concentrated developments. In contrast, Amsterdam's dispersed and variable road maintenance projects are ineffectively served by a single hub, which risks operational bottlenecks and inefficiency.

5.2.2. Decentralized: Importance of Proximity

In urban freight logistics, a centralized and clustered distribution system is often presented as a benchmark for efficiency, theoretically leading to shorter trips and optimized loads, especially when integrated with multimodal transport (Aljohani & Thompson, 2016). In contrast, many cities experience 'logistics sprawl,' which is the unplanned and dispersed movement of facilities into suburban areas. This sprawl is widely documented as inefficient, increasing total vehicle kilometers, CO_2 emissions, and creating a disconnect from urban labor markets.

A well-planned centralized system could be effective, but its universal applicability is challenged by specific demand profiles. The case of Amsterdam's road maintenance, which involves a high volume of small, geographically scattered projects, provides a clear exception. In this study's Centralized model, routing all materials to a single hub, even an optimally located one, proved highly inefficient, generating the largest transport burden (1.7 millions t-km). The distributed nature of the demand itself overwhelmed the theoretical benefits of centralization. For this type of many-to-one problem, a single hub acts not as a point of efficiency, but as a bottleneck. Not only it forces long and inefficient cross-city journeys, it also risks overloaded a single hub to process materials for city-wide projects.

The solution for this kind of distributed demand is therefore not a single central hub, but a planned, decentralized network. The superior performance of the 5-CCH Decentralized model, which reduced t-km by 32%, stems from its strategic alignment with this demand pattern. By placing multiple hubs within the city's key material hotspots (as identified in Figure 4.5), the network functions as a series of smaller, more efficient 'mini-centralized' systems. This approach avoids the instability of sprawl while also overcoming the limitations of a single central hub for this specific use case.

This Decentralized strategy aligns with the recommendation from Aljohani and Thompson (2016) to re-evaluate planning policies and actively preserve freight-intensive land within urban areas. Rather than one large preserved area, the result indicates the need for several strategically located sites. This approach establishes a planned network of circular material districts that are integrated into the city's layout. This creates a planned network of circular material districts integrated into the city's layout and provides hubs that could also serve as anchors for last mile logistics, as explored in the Hub-and-Spoke model.

5.2.3. Hub-and-Spoke: Value of Consolidation

The Hub-and-Spoke model, while a widely recognized logistical approach, introduces a well-documented trade-off. As noted by Burns et al. (1985) and Hall (1987), this configuration often leads to longer travel distances and higher handling costs due to indirect routing through consolidation points. This study confirms that finding: the refined 6-TSS Hub-and-Spoke model resulted in a 22% higher t-km value than the Decentralized network, clearly quantifying the transport inefficiency.

However, evaluating the model solely on transport t-km overlooks its broader strategic value. In a complex urban environment like Amsterdam, the increased transport effort could be seen as a strategic investment in building a structured, integrated network that addresses key challenges such as logistics sprawl. The Hub-and-Spoke system, with its network of consolidation points, provides the infrastructure needed to re-integrate logistics into dense urban areas, as recommended by Aljohani and Thompson (2016). Its advantages, including improved planning and modal integration, become practical solutions for many pressing urban logistics challenges.

Most notably for Amsterdam, this model enables regulatory compliance and efficient last mile delivery. The TSSs in the network function as Micro Urban Consolidation Centres (MUCCs) or Urban Logistics Spaces (ULSs), as described by Aljohani and Thompson (2016). These sites act as transshipment points, separating long-haul and last mile transport. Larger vehicles could deliver materials to TSSs outside the Zero-Emission Zone (ZEZ), while smaller, emission-free vehicles handle the final delivery. This two-stage system is not just an optimization but a practical necessity for future-proofing city logistics.

Finally, a Hub-and-Spoke network enhances overall system resilience and provides a framework for structured, rather than sprawling, growth. The distributed nature of the TSSs offers operational flexibility; if one site is at capacity or inaccessible, material flows could be temporarily held or rerouted to another node in the network. This distributed buffering capacity mitigates risk and ensures a more reliable supply of materials (Alumur et al., 2012), preventing single-point-of-failure bottlenecks and supporting a robust supply chain. By defining a clear hierarchy of hubs (CCHs) and spokes (TSSs), the model establishes a planned structure that avoids the uncoordinated growth and suboptimal integration typical of logistics sprawl.

5.3. Insights for Facility Location

The analysis of the different network configurations leads to more than just a performance comparison. By revealing a set of fundamental principles for strategic siting, it provides a direct answer to Sub-RQ1: *"What are the key criteria for CCH location?"* These principles, derived from the iterative modeling process, offer a transferable framework for planners. This section will synthesize these findings into two core principles: the first addressing the demand-centric criteria for siting permanent CCHs, and the second addressing the network-oriented logic required for temporary TSSs.

5.3.1. Criteria for CCH Siting

The first and most critical principle for the strategic siting of permanent Circular Construction Hubs (CCHs) is that the process must be fundamentally demand-driven. However, this must be balanced against a second, equally critical principle derived from the practical realities of a dense city: the feasibility of spatial scale and land availability. A GIS-based suitability analysis, which includes screening for compatible land use, sufficient parcel size, and buffer zones, is a necessary starting point, but it is not sufficient on its own. The success of a CCH network depends on placing hubs in close proximity to the hotspots of material generation.

This principle was revealed through the iterative process of this study. The initial 3-CCH network was designed based on a conventional suitability analysis, identifying large, appropriately zoned industrial parcels. However, the evaluation of this initial design (Activity 5) revealed a shortcoming: a high workload imbalance, with one hub at Omval/Overamstel handling over 60% of the network's transport effort.

The cause of this issue was a spatial mismatch between the location of the hubs and the distribution of demand. The analysis of the municipal project data, visualized as a tonnage heatmap (Figure 4.5), showed that the highest concentrations of upcoming road maintenance were in the Zuid and Zuidoost districts. The initial hub network left these areas underserved. The key insight in the redesign phase (Activity 3, Loop) was the decision to prioritize this demand data over generic suitability. New CCHs were strategically placed at Westlandgracht and Nellestein not just because they were on industrial land, but because they were situated at the epicenter of projected material flows. This demand-centric adjustment directly resolved the workload imbalance and improved network efficiency.

The key takeaway, therefore, is twofold. First, establishing a CCH network must begin with a thorough Material Flow Analysis (MFA) to map where target materials originate and are needed. Choosing sites without this understanding risks creating costly, underused infrastructure, while a demand-driven approach ensures the network delivers the greatest logistical and environmental benefits. Second, the design of this network must be grounded in the pragmatic reality of land scarcity and scale. Storage is considered a 'very low form of use' (E2, Appendix C.2) that competes directly with high-value functions like housing. This means that a network of fewer, very large hubs may be less feasible than a network of more numerous, medium-sized hubs that align with a reasonable available plot size.

Therefore, the recommended strategic process for sitting CCHs could be summarized as follows:

1. **Assess Spatial Scale:**
   Begin by determining a feasible and reasonable plot size for hub facilities based on the city's specific land availability and costs, in consultation with municipal planners.
2. **Prioritize Demand Mapping:**
   Begin by conducting a thorough MFA to identify and map the geographic hotspots of material generation.
3. **Identify Candidate Zones:**
   Find candidate locations within or as close as possible to these high-demand zones. This search should be filtered by the necessary baseline criteria.
4. **Apply Suitability Filters:**
   Within the candidate zones, filter for specific parcels that meet requirements (suitable zoning, sufficient size, safety buffers).
5. **Evaluate:**
   If multiple suitable sites are found, evaluate them based on their ability to serve the demand cluster efficiently, considering factors like major road access and potential for network-wide balance.

To further enhance the robustness of this process, expert feedback (Expert 3, Appendix C.3) introduced the valuable concept of identifying 'no-regret' solutions. This advanced approach would involve running multiple optimization scenarios with varying assumptions (e.g., different material flow projections, cost structures, or policy constraints). Industrial sites that are consistently selected as optimal across a wide range of scenarios can be considered highly robust 'no-regret' locations. Pinpointing these locations is extremely valuable, as it gives municipalities strong confidence in reserving these specific sites for future circular activities, knowing they are strategically sound under various potential futures.

5.3.2. Considerations for TSS Placement

Although permanent CCHs should be located as close as possible to material demand, the approach to siting TSSs requires a more nuanced and network-oriented rationale. The most effective TSS location is not simply the one closest to a project; it is the one that optimizes the total compounded transport effort of the entire two-leg journey (Project to TSS to CCH).

This network-oriented rationale is further complemented by considerations that define both the nature and the necessity of a TSS. Expert insight from the City of Amsterdam suggests that the decision to use a formal TSS is highly dependent on the required storage duration. For very short-term needs, perhaps under three months, materials might be managed hyper-locally within a project's neighborhood itself. A formal TSS becomes necessary for longer-term storage scenarios, acting as an intermediary before materials are sent to a permanent CCH for processing (E2, Appendix C.2). Furthermore, the physical characteristics of a TSS are a critical, non-trivial detail. As the expert noted, a TSS could range from a few designated parking spaces to a properly secured facility with a fence, a suitable floor for heavy materials, and on-site guarding. These factors highlight that the successful deployment of a TSS network requires a level of detailed, site-specific planning that goes beyond the strategic scope of this thesis but is essential for real-world implementation.

This principle was demonstrated by the inadequate performance of the initial Hub-and-Spoke model. In that design, the eight TSS locations were selected based on more streamlined suitability analysis. This approach, however, proved to be suboptimal The evaluation revealed that several of these TSSs, while close to their collection points (Leg 1), created highly inefficient and long second-leg journeys to their designated CCH. This significantly increased the overall system tonne-kilometers, negating the potential benefits of consolidation.

The insight gained from this study's algorithmic approach is that designing an efficient collection network requires simulating the entire system's performance. The Greedy Heuristic succeeded by selecting sites based on their contribution to the total network efficiency, not just individual leg distances. This provides a clear framework for siting TSSs to manage the reverse supply chain. However, expert insights suggest that in a fully operational system, these facilities would also play a critical role in the forward supply chain. As suggested by expert in road maintenance and circularity (Expert 1 or E1, Appendix C.1), a key function for such local hubs would be to act as distribution depots for processed, project-ready materials. This integrated vision, in which local sites manage both incoming and outgoing flows, creates a complete, closed-loop system.

Therefore, the process for identifying and selecting an effective set of TSSs requires a holistic network analysis. The recommended approach could be summarized in the following steps:

1. **Define the Anchor Network:**
   First, establish the locations of the permanent CCHs that will serve as the final destinations for the consolidated materials.
2. **Generate a Candidate Pool:**
   Identify a broad set of potential TSS locations based on basic criteria (e.g., small industrial plots, brownfield sites, depot areas) within the operational range of the CCHs and project clusters.
3. **Employ Algorithmic Selection:**
   Utilize a network optimization tool or heuristic algorithm (like the Greedy Heuristic used in this study) to iteratively select TSS locations from the candidate pool.
4. **Evaluate:**
   The generated list of top-performing locations should be subjected to a final real-world feasibility check to ensure practical and operational suitability.

5.4. Amsterdam Feasibility

Demand-driven siting and network optimization offer an effective general framework; however, their practical implementation depends on the unique spatial, operational, and political realities of each city. This section evaluates the feasibility of the proposed network specifically within the context of Amsterdam. It completes the answer to Sub-RQ2 by examining how real-world variations in assumptions, such as the current infrastructure, operational models, regulatory landscape, and governance structures, affect the ultimate effectiveness of theoretically optimized networks.

Drawing on quantitative analysis of the current infrastructure and qualitative insights from industry experts, this section translates the theoretical network design into a functioning, real-world system. In doing so, it demonstrates that a network's true viability is determined not by logistical metrics alone, but by its alignment with the complex realities on the ground.

5.4.1. The Current Infrastructure

An evaluation of any proposed network must begin with the current operational reality in Amsterdam. Recently, the city enacted a crucial reform, the *Modemaatregel*, which fundamentally reshaped its material management system (E1, Appendix C.1). This policy shifted the ownership of all salvaged paving materials to the municipality, establishing traceability and centralized control. This addressed a major governance challenge by replacing a previously opaque system, in which contractors took ownership of old materials, with a model of centralized governance. This reform was essential for mitigating the risks of material loss inherent in a complex organization (E2, Appendix C.2).

To operationalize this policy, contractors are now required to deliver all specified materials to one of two designated hubs: a contractor-run facility at Sluispolderweg or the primary municipal Stadswerken hub at Theemsweg. A simulation of this current two-hub network using this study's project data reveals a total system-wide transport effort of approximately 3.3 million tonne-kilometers (Table 5.1).

Table 5.1: Statistics of existing network calculated using future road maintenance data.

CCH Location	Total Distance (km)	Mean Distance (km)	Projects Served (#)	Total Tonnage (t)	Total Tonne-km (t-km)
Sluispolderweg	683.14	8.99	76	82,567	773,938
Theemsweg	2,258.11	9.73	232	242,380	2,560,870
Totals	**2,941.25**	–	308	324,947	**3,334,808**

The analysis shows a significant spatial imbalance, with the Theemsweg hub handling nearly 75% of the total tonnage. This disparity forces it to serve projects from across the entire city, resulting in long average haul distances (9.73 km) and a transport effort of over 2.5 million t-km for that facility alone (see Figure 5.1). This is a real-world manifestation of the hub imbalance problem that was diagnosed in this thesis's initial modeling phase.

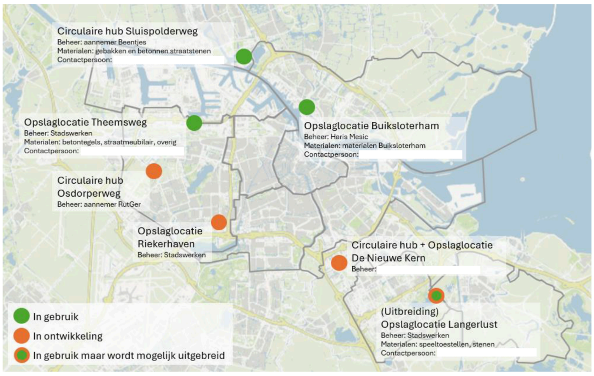


Figure 5.1: Existing hubs in the City of Amsterdam (Source: Municipality of Amsterdam).

Amsterdam's circular infrastructure is rapidly evolving, with new sites being developed and existing hubs considered for expansion (Figure 5.1). This shift reflects recognition of the current two-hub system's limitations and a move toward a more distributed network, aligning with this thesis's recommendation for strategically placed hubs to improve efficiency.

While the city is expanding its network, relying on ad-hoc growth risks new inefficiencies. The proposed 5-CCH Decentralized network offers a strategic alternative, demonstrating a potential 65% reduction in transport effort compared to the current baseline. Rather than replace ongoing efforts, it provides a blueprint to guide expansion toward a spatially optimized, policy-aligned system that maximizes logistical and environmental benefits.

Table 5.2: Statistics of existing network calculated using 7 hubs.

CCH Location	Total Distance (km)	Mean Distance (km)	Projects Served (#)	Total Tonnage (t)	Total Tonne-km (t-km)
Buiksloterham	388.84	4.14	94	97,749	370,566
De Nieuwe Kern	345.50	4.16	83	70,592	249,232
Riekerhaven	223.13	3.60	62	61,821	190,816
Langerlust	139.45	4.10	34	62,261	251,689
Theemsweg	91.98	3.41	27	16,839	50,895
Osdorperweg	31.70	2.26	14	15,642	35,436
Sluispolderweg	4.32	4.32	1	43	186
Totals	**1,224.92**	–	315	324,947	**1,148,820**

5.4.2. The Spatial Scale

The expert evaluations, particularly from the municipal advisor (E2), challenged the spatial scale assumed in the refined network models. According to the city's estimates, achieving an 85% reuse rate for paving bricks would require approximately 50,000 m² (5 hectares) of storage. This demand contrasts sharply with the on-the-ground reality that a feasible plot size for a single hub in land-scarce Amsterdam is 5,000–7,000 m² (E2, Appendix C.2). This disparity prompted a key question: What network scale is truly required to meet the city's ambitions, and how would such a network perform?

A capacity-based analysis assumed a 60% usable area ratio on a 5,000 m² plot, giving each hub about 3,000 m² of effective storage. The calculation indicated that roughly 17 such hubs would be needed to handle the volume of this single material stream.

$$\text{Number of hubs required} = \frac{\text{Total storage demand}}{\text{Feasible plot size} \times \text{Usable area ratio}} = \frac{50{,}000\,\text{m}^2}{5{,}000\,\text{m}^2 \times 0.60} \approx \mathbf{17} \quad (5.1)$$

This requirement implies a significantly larger and more distributed network than the 5-CCH model. To evaluate its logistical performance, a simulation was run using an adapted version of the Greedy Heuristic algorithm (detailed in Appendix B.1). For a single-tier decentralized network, the algorithm optimized direct project-to-hub routes rather than a two-leg journey. It prioritized iteratively selecting the hub that maximized total tonnage served, while secondarily minimizing transport effort (t-km). The performance of this scenario, when compared to the other network configurations, is summarized in Table 5.3.

Table 5.3: Network Configuration Performance Comparison

Network Configuration	Number of Hubs	Total t-km	Avg. Distance (km)	Reduction from Baseline (%)
Real-World Baseline	2	3,334,808	9.36	0%
Refined Decentralized	5	1,166,416	3.91	65%
Hyper-Local	17	574,322	2.03	83%

As the data shows, the 17-hub network achieves a total transport effort of 574,322 t-km, an 83% reduction from the current baseline and nearly a 50% improvement over the refined 5-hub model. This result provides quantitative support for expert observations that a more granular network can offer greater transport efficiency. The spatial logic behind this performance, a highly distributed network closely aligned with material demand hotspots, is illustrated in Figure 5.2.

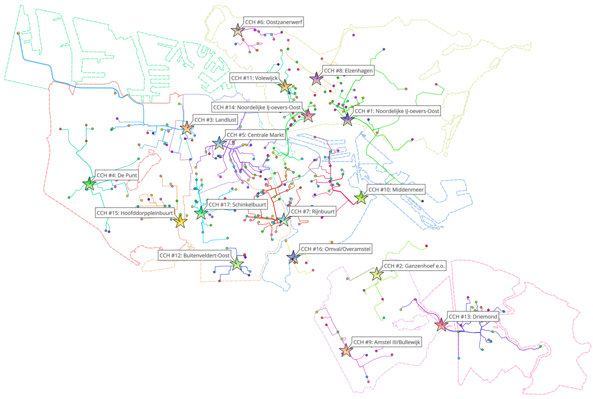


Figure 5.2: Spatial layout of the optimized 17-hub Hyper-Local network.

However, this logistical optimum must be balanced against practical feasibility. While the shorter haul distances and balanced spatial coverage shown in Figure 5.2 offer clear benefits, acquiring, staffing, and coordinating seventeen facilities presents a substantial operational and governance burden. As municipal experts note, each additional transfer point is a "complicating factor" that increases the risk of system failure (E2). This analysis leads to a nuanced conclusion: the 17-hub network, while representing the theoretical optimum for transport efficiency, is not immediately implementable solution due to substantial operational and governance challenges. Its primary value lies in demonstrating the potential of a highly distributed system. This finding points out that the optimal path forward is not a single, static configuration, but a scalable, multi-tier, hybrid strategy. The subsequent sections synthesize these findings to establish the guiding principles for such a network and outline its broader implications for enabling a high-value circular economy.

5.4.3. Operational Feasibility

Beyond the strategic placement of hubs, the network's feasibility depends on a clear and practical blueprint for how materials will flow through the system. This is particularly critical in Amsterdam, where the inability to stockpile materials on dense urban worksites is a major barrier to reuse (Ajayi et al., 2015; de Groot, 2024). This constraint forces contractors to remove salvaged materials almost immediately, creating a continuous flow of mixed, unsorted materials that would overwhelm a simple point-to-hub model. A more sophisticated, multi-stage workflow is therefore required, breaking down the reverse logistics process into distinct, manageable steps.

The Hub-and-Spoke model, therefore, enables an essential, two-tiered operational system where CCHs and TSSs serve distinct yet complementary roles. This multi-stage process is not merely a theoretical construct; it aligns directly with expert visions for a future-proof circular system. As described by an expert (E1, Appendix C.1), its true value lies in managing the critical temporal mismatch between demolition and construction schedules. This conceptual model is illustrated in Figure 5.3.

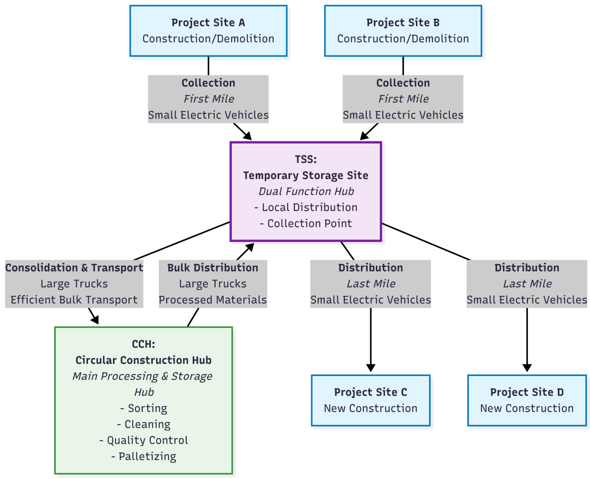


Figure 5.3: Conceptual diagram of the two-tiered model, illustrating the TSS as both collection and distribution point.

This dual-function model, illustrated in Figure 5.3, is made possible by a detailed, multi-stage material handling process. Industry professionals (Expert 4 or E4, Appendix D) further confirm that the inability to stockpile materials on dense urban worksites forces contractors to remove salvaged materials almost immediately after extraction. As a result, contractors must manage a continuous flow of mixed, unsorted materials, which presents a significant logistical challenge. In this context, a simple direct point-to-hub model is less suitable, as it would overwhelm a central processing facility with unsorted debris.

A more sophisticated, multi-stage workflow is therefore required. Figure 5.4 provides a flowchart of this operational sequence, showing how the network efficiently handles this flow: from immediate on-site removal, through local triage at a TSS, to final value-adding processing at a CCH. Figure 5.4 provides a detailed flowchart of this specific operational sequence.

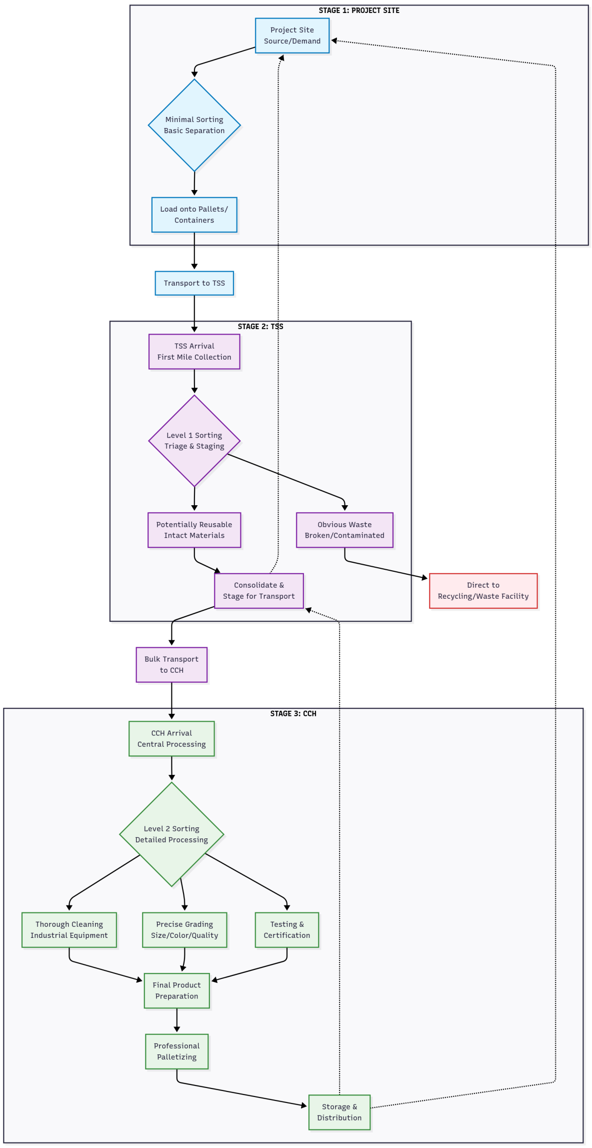


Figure 5.4: A detailed flowchart of the multi-stage material handling process within the reverse logistics flow.

As the diagram demonstrates, this model creates a structured pathway that enable on-site efficiency while centralizing the complex, value-adding activities. The process could be understood in three distinct stages:

Stage 1: On-Site Collection

The process begins at the project site, where the primary goal is efficient and careful removal of materials. Instead of complex on-site sorting, which is slow and costly, crews perform only minimal separation to prepare materials for transport (Stage 1). This removes a significant logistical burden from the active worksite, allowing contractors to use smaller, more flexible vehicles to make short trips to their nearest TSS. This initial step aggregates materials from many dispersed sources into a manageable location, which reduces clutter and opens up valuable space at the constrained maintenance site.

Stage 2: Local Triage and Consolidation at the TSS

The TSSs function as first mile collection, staging, and triage points. Upon arrival (Stage 2), materials go through Level 1 Sorting. Here, waste and contaminated materials are segregated and sent directly to an appropriate recycling or disposal facility, reducing unnecessary transport of non-reusable materials to the main hub. The remaining potentially reusable materials are then consolidated for more cost-effective bulk transport to a central CCH. This triage stage is also where a temporal decision is made. As highlighted by a municipal expert, the required storage duration determines the material's path: materials needed within a short timeframe might be managed locally, while those requiring longer-term storage are routed to the permanent CCH network (E2, Appendix C.2).

Stage 3: Centralized Processing and Distribution at the CCH
The CCH serves as the network's central processing facility, where value-adding work occurs (Stage 3). Materials arriving from the TSSs go through Level 2 Sorting, which includes activities like industrial cleaning, quality grading, and certification. This centralized approach is essential for transforming inconsistent salvaged materials into a standardized, reliable product that clients could trust. After final preparation, the materials are ready for distribution. As the flowchart indicates, these certified, high-quality materials could then be sent from the CCH (either directly or through the TSS network for last-mile delivery) to new construction projects, thus closing the loop.

While this model presents a clear workflow for reverse logistics, expert feedback (E1, Appendix C.1) suggests a more sophisticated role for the TSS in forward logistics. As designed in the operational flowchart (Figure 5.4), the TSS functions as a last mile distribution center, a role that is key to managing the critical temporal mismatch between demolition and construction schedules. This allows a project to "pull the materials whenever they need it" from the nearest TSS, providing a just-in-time supply of reused materials without requiring extra storage on the construction site itself.

Implementing this multi-stage model introduces significant trade-offs, most notably increased handling complexity. As stated by the expert from municipality (E2, Appendix C.2), every transfer point introduces a risk of system failure, where "responsibility of that material... it's either lost or it is not taken care of very well". Successfully managing this complexity is therefore non-negotiable and requires a sophisticated digital inventory management system. For example, the 'Circular Hub Module' as part of the Construction Logistics Control Tower (CLCT) discussed by Harmelink et al. (2025) is specifically designed to coordinate these flows. Such digital infrastructure is essential to ensure seamless integration, real-time data sharing, and efficient coordination, turning a potentially chaotic process into a structured and reliable system.

5.4.4. Policy Alignment

The strategic value of a redesigned logistics network extends beyond circularity and cost savings; it is fundamentally linked to Amsterdam's ambitious environmental and air quality goals. The city is implementing a phased, two-tiered system of vehicle access restrictions that presents significant operational challenges for the construction sector and underscores the need for a more sophisticated logistics model (Figure 5.5).

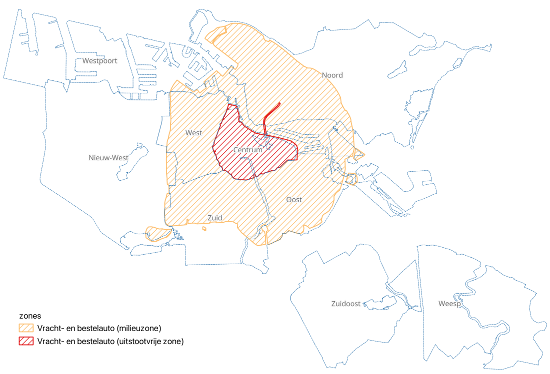


Figure 5.5: *Milieuzone* (orange) and *uitstootvrije zone* (red) in Amsterdam.

The first tier, the city-wide *milieuzone*, covers the area within the A10 ring road and already limits access for older, more polluting diesel vehicles. Most modern construction trucks (Euro 6) are currently allowed to operate in this zone, but having such a zone sets a clear example of controlling access based on vehicle type. The second, more impactful tier is the progressive implementation of the *uitstootvrije zone* (zero-emission zone). Beginning in 2025, all new commercial vehicles entering the city center must be fully emission-free, and by 2028, this requirement will apply to all commercial vehicles within the expanded zone (Gementee Amsterdam, n.d.). This policy makes the traditional logistics model, in which large diesel trucks transport materials directly between city worksites and peripheral hubs, increasingly infeasible. The current ad-hoc system does not provide a solution for this regulatory shift.

The Hub-and-Spoke network configuration provides a practical response to these challenges. Its two-tiered structure is well suited to this regulatory environment, with Temporary Storage Sites (TSSs) playing a key role. These TSSs can be located at the edge of the zero-emission zone, serving as transshipment points where materials are moved from standard long-haul trucks to a fleet of smaller, fully electric vehicles. This operational model addresses the immediate access issue and supports the expert view that a future-proof system benefits from a network of more local storage hubs to facilitate distribution (E1, Appendix C.1).

By assigning the task of managing the ZEZ boundary to the flexible TSSs, the network makes it possible for the permanent, high-investment CCHs to be located based on long-term considerations, such as proximity to areas with higher material demand. This approach is relevant, as municipal experts observe that the ZEZ boundary may be a transitional policy, with zero-emission requirements potentially expanding city-wide in the coming years (E2, Appendix C.2). In this way, the Hub-and-Spoke system is more than just a logistical choice; it offers a framework that helps the construction sector comply with current regulations while also considering longer-term goals related to circularity and climate targets.

5.4.5. Governance Viability

The long-term success of a circular construction hub (CCH) network depends on a viable governance structure and a sound economic model, not solely on spatial optimization or transport efficiency. As discussed in Chapter 2, implementing a Circular Economy (CE), especially for high-value reuse, necessitates systemic coordination, long-term planning, and the alignment of public and private sector incentives (Reike et al., 2018; Potting et al., 2017). In Amsterdam, where land constraints, policy ambitions, and infrastructure fragmentation coexist, governance is a critical enabling factor.

Both expert interviews and recent literature suggest that neither a purely public nor a purely private model could effectively support a CCH system. OECD (2024) and expert feedback (E1, Appendix C.1) recommend the Public-Private Partnership (PPP) contract type. Fully public models are sometimes perceived as less agile or limited in capital, often due to administrative processes or budget constraints, though this could vary depending on local circumstances. Private systems, on the other hand, could present challenges such as fragmentation and potential policy misalignment. A PPP, therefore, may offer a balanced approach by combining public strategic authority with private operational capacity. In such a partnership, the municipality would provide the strategic vision, set policies like reuse targets, and potentially offer access to land. The private sector, mainly large framework contractors, would bring operational expertise, invest in equipment, and manage daily logistics.

However, a critical barrier to such partnerships is the lack of planning security for contractors. As highlighted by expert feedback (E1, Appendix C.1), private firms are hesitant to make significant capital investments without assurances of long-term material flow. The absence of guaranteed volumes and stable contracts increases risk, discouraging investment in hub models.

To address this, the city could design incentive structures that align public goals with private interests. Offering long-term service contracts or advantages in future tenders for contractors who invest in hub infrastructure could reduce perceived risk. This stable collaboration enables the necessary infrastructure for localized flows and real-time coordination, minimizing transport costs and making high-value reuse economically feasible.

The city could further leverage this thesis's findings to design a PPP that systematically reduces private investment risk. Endorsing the network of five CCHs and six TSSs, identified through spatial analysis, removes uncertainty about operational locations. Additionally, the city could use findings from Fröhling (2023) to set procurement goals, such as achieving a 58% reduction in Global Warming Potential (GWP) for concrete tiles. This allows operators to build business cases around delivering high-value environmental services.

With reduced investment risk, the PPP could focus on aligning incentives for the network's intended operation. The CCH network provides the infrastructure for sorting, storage, and quality control required for ambitious environmental scenarios. Green Public Procurement (GPP) tenders could reward contractors who use this network effectively. The PPP also provides a framework for managing the two-tiered Hub-and-Spoke system, which is essential for compliance with Amsterdam's Zero-Emission Zone, where the city sets the rules and private operators manage last-mile delivery.

5.5. Enabling High-Value Circularity

The Circular Economy (CE) emphasizes the high-value reuse of materials, yet the construction sector often defaults to low-value recycling or linear disposal. The transition to a high-value CE in this sector is stalled not by a single obstacle, but by an interconnected system of economic, logistical, and risk-related barriers. Without targeted intervention, the linear path remains simpler, cheaper, and more predictable. The upfront costs of selective deconstruction (Dantata et al., 2005; Harsunen et al., 2025) are compounded by the logistical complexity of moving, sorting, and storing salvaged materials (Ajayi & Oyedele, 2018; Ghafoor et al., 2024). This complexity creates risks for the end-user (client), who perceives reused materials as prone to damage, inconsistent in quality, and uncertain in supply (E4, Appendix D). As noted by an expert, ambiguity in the process leads to inaction and a default to the linear option (E2, Appendix C.2).

This study argues that a strategically designed logistics network is the essential enabling mechanism to break this cycle. By creating an integrated reverse logistics system, a network of circular construction hubs (CCHs) and temporary storage sites (TSSs) could simultaneously tackle the root causes of cost, inefficiency, and risk. It transforms the ad-hoc, high-risk process of reuse into a reliable, streamlined, and economically viable system.

5.5.1. Tackling the Core Drivers

The primary economic barrier to reuse is cost, which is largely driven by logistics. This study demonstrates that a well-designed network could directly mitigate these costs at every stage. Transportation is often the largest single cost factor, making salvaged materials unviable over long distances, as noted by Ghafoor et al. (2024). In addition, every kilometer traveled and every handling step increases the risk of material damage. The refined 5-CCH Decentralized network addresses this challenge by applying the Proximity Principle, reducing total transport to 1.17 million tonne-kilometers, which represents a 65% reduction from the baseline. This not only significantly cuts fuel costs and emissions but also serves as an effective strategy for preserving material integrity. In this way, it directly responds to clients' concerns about receiving damaged goods.

Centralizing operations for efficiency and scale is also crucial. On-site sorting is disruptive and expensive, while off-site storage adds additional transport legs, as discussed by Ajayi and Oyedele (2018). The proposed CCHs, such as those at Havens-West or Omval/Overamstel, provide dedicated spaces for efficient, large-scale sorting and processing. This centralization creates economies of scale that lower per-unit costs. The Hub-and-Spoke model further enhances efficiency by using TSSs as local triage points, ensuring that CCHs receive a higher-quality input stream. This allows the hubs to focus on value-adding activities such as certification and industrial cleaning, which ultimately increases the yield of high-value materials recovered.

Synchronizing supply and demand is another key factor. The mismatch between when materials are salvaged and when they are needed creates inventory costs and supply uncertainty, as highlighted by Pronk et al. (2022). A network of strategically located TSSs, capable of capturing over 90% of material flow, acts as a city-wide system of storage buffers. This approach reduces supply chain risks for individual projects by creating a larger, more liquid, and diverse city-wide inventory. As a result, contractors are provided with the supply security they require.

5.5.2. Building Market Confidence

As highlighted in the discussion with the industry professional (E4, Appendix D), 'The Client is King' and often rejects reusable materials due to perceived risks of damage, inconsistency, or future maintenance needs. These risks, however, are not limited to the materials themselves; procedural uncertainty is equally significant and acts as a primary driver of inaction. As highlighted by a municipal expert, the system often breaks down when faced with a series of simple yet unanswered questions: 'How long could I store my materials?', 'Who is responsible if they are lost?', and 'Is the storage site secure?'. This unpredictability makes contractors hesitant to adopt circular practices, causing them to default to the linear path of least resistance (E2, Appendix C.2).

The structure of the network is fundamental to building the confidence needed to overcome these barriers. Transitioning from supply uncertainty to supply security, a planned network replaces the risks inherent in ad-hoc stockpiling with greater choice and reliability. Both network models discussed here transform disparate material sources into a dependable city-wide inventory. Notably, the Hub-and-Spoke model, with its additional layer of TSSs, offers the highest degree of supply security by creating a distributed and liquid inventory, thereby increasing the probability of sourcing the necessary volume and variety for any given project.

Addressing the issue of inconsistent quality, client rejection is often rooted in fears of inconsistency. The two refined network models approach this challenge in different ways. The Decentralized network offers a simple and low-risk approach that minimizes potential handling damage through its direct and shorter routes. The Hub-and-Spoke network, in contrast, provides a more sophisticated system that is not intended to create quality but to enable higher-value reuse by introducing critical points of control and sorting. Its two-stage process, which includes initial triage at the TSS and specialized processing at the CCH (see Figure 5.4), creates a formal pathway to filter out low-grade materials early and to identify high-potential stock for value-adding activities such as cleaning and certification. This approach directly addresses the trade-off between higher operational complexity and the potential for a greater yield of certified and reusable products. It is therefore a strategic choice aimed at creating a reliable supply of high-quality secondary materials that could genuinely compete with their virgin counterparts. Collectively, these mechanisms help to reduce perceived risk for clients and build the market confidence necessary for circular practices to take root.

5.6. Strategic Trade-Offs

The analysis reveals that designing a circular logistics network is not about finding a single "best" solution, but about navigating a series of strategic trade-offs. This finding is strongly supported by expert interviews, which illustrate a system evolving from ad-hoc initiatives to a more deliberate, strategic infrastructure. An expert noted that the city's first circular hubs were not the product of top-down strategy, but the result of "first mover" contractors, and that current efforts represent "the attempt to be more strategic about it" (E1, Appendix C.1). This study, therefore, evaluates the trade-offs inherent in that strategic next step. The core decision lies between prioritizing cost-efficiency and operational simplicity versus system-wide value capture and supply chain resilience. This choice is summarized in Table 5.4.

Table 5.4: Comparison of strategic trade-offs between configurations.

Feature	Decentralized	Hub-and-Spoke
Transport Effort	Low; direct point-to-hub flows.	High; increase due to multi-layer structure.
Key Advantage	Low transport cost and number of handoffs, reducing risk of system failure and material damage.	Providing infrastructure for mode shifts, while also offering inventory buffering and enhancing system resilience.
Key Challenge	May be less adaptable to complex urban access restriction without adding further logistical layers.	The multiple handling steps add operational complexity and cost, creating more potential points of system failure.
Best Suited For	Cities where minimizing transport carbon and prioritizing a simple, direct, low-risk operational model is the absolute top priority.	Cities with complex access restrictions or a strategic need for a highly resilient, buffered inventory system, accepting higher operational complexity as a trade-off.

As the table illustrates, the decision requires policymakers and planners to consider the balance between quantifiable transport savings and the benefits of operational flexibility. The Decentralized network is optimized for tackling the two most immediate barriers to circularity: cost and risk. From an environmental perspective, transport's impact could be secondary to preserving the high embodied energy in materials. However, from a practical standpoint, "cost is super, super relevant for secularity" (E1, Appendix C.1). The primary reason circular ambitions fail, such as trucks returning empty instead of backhauling materials for recycling, is because the transport is "too expensive" (E1, Appendix C.1). The Decentralized model's 65% reduction in transport effort directly addresses this primary economic barrier. Simultaneously, its simple, direct flows address the profound operational risks of a complex system. As one expert from the municipality warned, every additional handling step is a "complicating factor" where materials could be lost or damaged (E2, Appendix C.2). The Decentralized model is therefore the most direct and lowest-risk approach.

Conversely, the Hub-and-Spoke network is a more complex model designed for a more sophisticated strategic goal: decoupling project timelines and maximizing system-wide material management. The strength of this model lies in the dual-function design of its TSS network, which serves as both a collection point for reverse logistics and a distribution hub for forward logistics. Expert insight (E1, Appendix C.1) confirms the critical importance of this structure, highlighting that the TSS's role as a post-processing distribution center is the key to solving the temporal mismatch between when materials are salvaged and when they are needed. However, this strategic advantage comes at the cost of the operational complexity that another expert considers a significant concern (E2, Appendix C.2). The model's viability thus depends on whether the benefits of a managed, resilient supply chain outweigh the costs and risks of its multiple handling steps.

Finally, this strategic choice must be understood within the constraints of scale and space. As the capacity-based analysis shows, the annual material volume may require a network significantly larger than either refined model. The simulation of the 17-hub "hyper-local" network, with its markedly superior transport efficiency (574,322 t-km), serves as a benchmark for the potential of a highly granular system. This does not negate the trade-off outlined above but sharpens it: while the 5-hub Decentralized model is highly efficient, it leaves notable efficiency gains unrealized, and the transport penalty of the Hub-and-Spoke model becomes even more pronounced against this benchmark. The choice of network configuration is therefore a high-stakes decision on how best to allocate scarce urban land to manage substantial material flows, balancing a pragmatic starting point with the ultimate efficiency objective.

5.7. Broader Implications

The findings of this research extend beyond the specific case of Amsterdam to provide a direct answer to Sub-RQ3: *"What key decision-making insights from this thesis could support the planning of CCH in other cities?"* The process of designing and evaluating a circular logistics network has revealed a set of transferable insights and practical methodologies that hold broader implications for both practitioners and academics. This concluding section summarizes these key contributions by dividing them into two distinct categories. First, it outlines the practical, strategic insights that could guide other municipalities in their planning efforts. Second, it highlights the distinct methodological contributions this thesis offers to the fields of urban planning and circular logistics research.

5.7.1. Key Decision-Making Insights

The findings of this thesis, though based on Amsterdam, offer transferable insights and a strategic framework that could help other municipalities and urban planners develop more efficient and robust circular construction logistics networks. The key insights are grounded not only in quantitative modeling but are validated and enriched by qualitative interviews with a circularity expert (E1), a municipal expert (E2), and an industry practitioner (E4).

The Demand-Driven Approach

One of the key insights from this research is that a successful hub network should be fundamentally demand-driven. A conventional, land-use-first suitability analysis can be a necessary but insufficient starting point. The initial network design, based solely on identifying available industrial land, was operationally imbalanced and inefficient. The improved performance of the refined network resulted from prioritizing where materials actually originate, consistent with foundational facility-location logic (Hakimi, 1964).

Expert insights indicate that this is not merely a logistical principle but an important driver of economic viability and client acceptance. As practitioners note, the client, often the ultimate gatekeeper of circularity, may “back up” if the “financial side” of it is too high (E4, Appendix C.3). Cost was described as a “super relevant” factor that often halts otherwise sound circular initiatives, such as backhauling materials for recycling (E1, Appendix C.1). Minimizing transport distances, often the dominant logistics cost, can therefore be one of the most direct levers for feasibility.

- *Key Insight:*
  Cities could begin not with a search for available land, but with a comprehensive Material Flow Analysis (MFA). Mapping hotspots of material generation can help ensure hub infrastructure is located where it is needed most. This demand-driven siting can directly reduce transport costs and support client acceptance. In competitive urban markets where storage is regarded as a “very low form of use” (E2, Appendix C.2), it can also respect land scarcity by avoiding investment in underutilized facilities.

Strategic Choice of Network Configuration

There is no single best network configuration; the optimal choice depends on a city’s specific goals and constraints. This research quantifies a classic trade-off in freight transportation theory. A Decentralized network is more effective in minimizing total transport distance and its associated costs. In contrast, a Hub-and-Spoke network incurs a measurable transport penalty but offers significant operational flexibility, including enhanced control and opportunities for modal integration, as discussed by Alumur et al. (2012) and Hall (1987). The expert evaluations and the sensitivity analysis conducted in this study indicate that this choice is not a simple binary decision, but rather a navigation across a spectrum of possibilities.

- *Key Insight:*
  Planners should weigh the trade-off explicitly, as different models address different challenges. The Decentralized model suits cases where minimizing transport costs and operational risk is the priority, with its simple structure reducing handling steps and the risk of material loss or damage (E2). The Hub-and-Spoke model can be justified when building a resilient, managed inventory sys-

tem to handle supply chain uncertainties and regulations such as Zero-Emission Zones, though this comes with higher operational complexity and risk (E2). The “Hyper-Local” model offers the theoretical optimum for transport efficiency, as shown by the 17-hub simulation, but governance and scale constraints make it a long-term goal rather than an immediate blueprint. A transferable lesson for other cities is that the most effective approach may be a hybrid strategy: start with a core network, such as the 5-hub Decentralized model, and apply principles from the other models to guide long-term evolution and the scalable deployment of smaller, flexible sites.

A Multi-Scalar, Tiered System

As highlighted by studies on two-stage city logistics (Aljohani & Thompson, 2016; Guerlain et al., 2019), a system with distinct roles for different facility types can be highly effective. This study’s findings, supported by expert feedback, indicate that a three-tiered structure is a robust operational model for dense urban areas, as it externalizes the on-site storage and sorting function that is often “not possible” on constrained worksites (E4, Appendix D).

- *Key Insight:*
  Define distinct roles for each tier of the network.
  - CCHs (Tier 1): These should be designed as centralized processing centers focused on value-adding activities like industrial cleaning, quality control, and certification. This transforms inconsistent salvaged materials into the standardized, reliable product needed to win client trust.
  - TSSs (Tier 2): These should be positioned as dual-function distribution satellites. In reverse logistics, they serve as initial triage points to filter out waste. In forward logistics, they hold pallets of project-ready materials for just-in-time delivery, providing the responsive inventory management needed to navigate unpredictable project timelines.
  - Staging Areas (Tier 3): For short-term needs, use small, temporary plots within neighborhoods to enable local reuse loops, as suggested by municipal experts (E2).

The Socio-Cultural Value

Beyond technical optimization, this research highlights an often-overlooked insight from municipal expert feedback: the socio-cultural value of hub visibility. This challenges the conventional view that industrial and logistical activities should be hidden on the urban periphery. Instead, it supports the strategic placement of certain circular facilities in visible locations to foster public awareness and accelerate the cultural shift towards a circular economy. Circular hubs can therefore serve a dual role: alongside their logistical function, they can symbolize a city’s commitment to sustainability.

- *Key Insight:*
  Incorporate “visibility” as a criterion in site selection, particularly for smaller, lower-impact facilities such as TSSs. As one municipal expert observed, when hubs are visible, they “become part of the DNA of the city,” whereas hiding all reuse activities means “nobody gets circularity in their head” (E2, Appendix C.1). By making the storage, sorting, and redeployment of materials a tangible part of everyday life, the concept of the circular economy becomes easier for the public to understand and support. In this way, a visible hub is not only a logistical node but also a pedagogical tool, serving as an educational and inspirational example of circular principles in action.

5.7.2. Methodological Contributions

In addition to its practical insights, this thesis offers three distinct methodological contributions to the fields of circular construction, urban logistics, and spatial planning. These contributions provide new or refined approaches for researchers and analysts in tackling similar complex problems.

Iterative Modeling

This thesis illustrates the practical demonstration of the Design Science Research Methodology (DSRM) framework, introduced in Chapter 3, for addressing complex spatial planning problems. The DSRM’s iterative design-evaluate-redesign cycle was helpful in identifying that an initial network, although logically designed using conventional suitability criteria, had an unexpected limitation: a significant hub imbalance that made it operationally impractical. This demonstrates that iterative evaluation against defined performance rules (Hub Balance, Spoke Efficiency, and Network Coverage) could be important for uncovering system weaknesses and improving the design toward a more workable network.

GIS-Based Heuristic

This research contributes a novel and practical method for optimizing the design of a multi-layer circular logistics network. The methodological contribution is not just a conceptual framework, but a custom-coded Greedy Heuristic algorithm that directly integrates real-world geospatial data to solve a complex siting problem. Key aspects include:

- **GIS and Network Integration:**
  The algorithm reads and uses geospatial data, linking spatial analysis with network planning.
- **Use of Actual Road Networks:**
  All distance and transport calculations are based on Amsterdam's actual road network, so the results reflect real travel routes and support better decision-making.
- **Fast and Practical Heuristic:**
  Designed for efficiency at the city level, the heuristic uses python's igraph libraries to quickly test many scenarios. This gives planners a practical and scalable tool that is faster and less demanding than traditional optimization methods.

Quantitative Framework for Network Reliability

This thesis introduces a quantitative framework that goes beyond simple efficiency metrics for evaluating circular economy infrastructure. The main contribution is a set of specific, rule-based requirements (Hub Balance (R-1), Spoke Efficiency (R-2), and Network Coverage (R-3)) that together assess a network's operational viability and overall health. Although metrics like tonne-kilometers capture overall efficiency, these rules are valuable for identifying specific weaknesses such as bottlenecks, underused assets, or nodes that add cost without real benefit. This provides a more complete and replicable toolkit for researchers to assess and compare the operational strength of proposed infrastructure designs.

6
Conclusion

6.1. Concluding Remarks

This thesis set out to address the challenge of logistical inefficiency in urban road maintenance by designing and evaluating strategic networks for circular construction hubs. Through the application of an iterative, data-driven methodology, this research moved from an initial, flawed network design to two refined, high-performing configurations. The analysis revealed a fundamental strategic trade-off between a transport-efficient Decentralized network and an operationally resilient Hub-and-Spoke system, demonstrating that the optimal solution is context-dependent. Finally, this research provides a clear framework and a set of transferable principles for strategically siting and configuring such networks.

6.1.1. Answer to Sub-RQ1

To summarize, this subsection focuses on the first sub-research question:

> *"What are the key criteria for CCH location and how can relevant data be utilized to identify candidate locations?"*

The study concludes that the key criteria for siting circular logistics facilities depend on the facility's role in the network. A multi-scalar approach is required, with distinct criteria for main hubs (CCHs) and Temporary Storage Sites (TSSs).

- **For CCH:**
  The analysis indicated that while baseline requirements such as (1) zoning compliance and (2) adequate parcel size are necessary prerequisites, a key criterion derived from the modeling is (3) demand-centric placement. Aligning hubs with empirically identified material hotspots was shown to be important for creating a balanced and efficient network. Expert evaluations add a fourth criterion: (4) feasible spatial scale. In a land-scarce context such as Amsterdam, the theoretical "adequate size" needs to be balanced against realistic land availability, which may favor a network of more numerous, medium-sized hubs rather than a few larger ones.
- **For TSS:**
  The quantitative analysis indicated that the criteria should priorities network performance, with two key factors being (1) total journey efficiency, where the full two-leg journey (Project to TSS to CCH) is optimized, and (2) proximity to project clusters to support sufficient throughput. Expert insights add a third, functional criterion: (3) storage duration. A distinction can be made between semi-permanent TSSs for longer-term consolidation, which require a holistic, network-based selection, and temporary, project-level staging areas for short-term, hyper-local reuse.

These criteria were operationalized through a data utilization framework that integrated:

- **GIS Suitability Analysis:**
  Using OSM and municipal data to assess spatial feasibility.

- **Network Analysis:**
  Using tools in QGIS to evaluate logistical efficiency by calculating actual road-network performance.
- **Iterative Evaluations:**
  Where the failure of the initial model against the requirements proved that criteria must be calibrated to prioritize demand distribution over generic suitability alone.

6.1.2. Answer to Sub-RQ2

In brief, the following addresses the second sub-research question:

> *"How can different CCH configurations be evaluated, and how do variations in assumptions impact their effectiveness?"*

The study demonstrated that different CCH configurations can be effectively evaluated and compared through an iterative, DSRM-based process of simulation and rule-based assessment.

- **How to Evaluate:**
  Configurations are initially modeled as distinct network types (Centralized, Decentralized, Hub-and-Spoke). Their performance is then assessed using key metrics, primarily total system tonne-kilometers (t-km). Importantly, these quantitative results are subsequently evaluated against a set of formal requirements (R-1, R-2, R-3) that consider factors such as workload imbalance and network inefficiency.
- **Impact of Variations:**
  The analysis indicates that configuration choice involves a strategic trade-off shaped by a city's priorities and assumptions about scale and complexity. A Decentralized network tends to minimize transport burden (t-km) and reduce risks from multiple handling steps. A Hub-and-Spoke network may suit priorities such as inventory management and regulatory compliance, though with higher transport costs. A Hyper-Local network offers the greatest transport efficiency in theory, but faces significant governance and operational challenges at scale.

6.1.3. Answer to Sub-RQ3

To restate, the focus here is on the third sub-research question:

> *"What key decision-making insights from this thesis can support the planning of CCH in other cities?"*

This thesis offers three transferable strategic insights that can guide municipalities and urban planners beyond Amsterdam in the development of more efficient and robust circular construction logistics networks.

1. An important insight is that a successful hub network is most effective when it is fundamentally demand-driven. The study demonstrates that while a conventional, land-use-first suitability analysis is a useful starting point, it may not be sufficient on its own. Initiating the process with a Material Flow Analysis (MFA) to map the geographic hotspots of material generation can help ensure that investment in hub infrastructure is directed where it is most needed.
2. The optimal network choice is a strategic trade-off rather than a fixed technical solution. Planners need to navigate the spectrum between a pragmatically efficient Decentralized network (low risk, low cost), an operationally resilient Hub-and-Spoke network (high control, high complexity), and a theoretically optimal Hyper-Local network (maximum efficiency, significant implementation barriers). An effective approach may be a hybrid, evolutionary strategy that balances these priorities over time.
3. A multi-scalar, three-tiered system can provide a robust operational model for complex urban areas. Tier 1 permanent processing hubs create standardized, trusted products; Tier 2 dual-function satellites (TSSs) manage local collection and distribution; and Tier 3 temporary staging areas enable hyper-local reuse loops.
4. The socio-cultural value of hub visibility is an important yet often overlooked factor. Strategically placing smaller hubs in visible locations, rather than relegating them to the urban periphery, can

make circularity a tangible part of city life. This visibility helps build the public awareness and support needed to sustain a long-term transition to a circular economy.

6.1.4. Answer to Main-RQ

The answers to the sub-research questions above collectively inform and form the basis of the response to the main research question:

> *"How can Circular Construction Hubs be strategically located and configured to support material reuse in urban road maintenance?"*

This thesis concludes that Circular Construction Hubs can be strategically located and configured through a multi-scalar, demand-driven process that supports the development of a hybrid, scalable network model. Strategically, facility placement should be driven by demand rather than land availability, beginning with a Material Flow Analysis (MFA) to locate permanent, high-investment hubs at material generation epicenters and smaller, flexible sites near local demand clusters.

Functionally, the optimal configuration is a three-tiered system with specialized roles: (1) permanent, medium-sized processing hubs (CCHs) producing standardized, high-quality outputs; (2) dual-function consolidation and distribution sites (TSSs) managing regional logistics; and (3) temporary, project-level staging areas enabling hyper-local reuse.

There is no single configuration that fits all contexts. The optimal solution is an evolutionary strategy, beginning with a pragmatic, low-risk Decentralized network of core hubs to maximize immediate transport efficiency, then expanding towards a more resilient Hub-and-Spoke system by adding TSSs to address operational complexities such as Zero-Emission Zones and inventory management. This approach enables cities to move beyond ad-hoc solutions, designing logistics networks that are strategically aligned with local priorities and capable of supporting a resilient, high-value circular supply chain.

6.2. Limitations of the Study

While this research provides a data-driven framework for strategic siting, its findings should be interpreted within the context of several limitations. These limitations, which were necessary to maintain a manageable scope, also offer clear directions for future research. The limitations can be categorized into three main areas: modeling assumptions, data constraints, and scope boundaries.

Modeling

The analytical model makes several simplifying assumptions about logistics operations. First, it assumes a unidirectional material flow (Projects to TSS to CCH or Project to CCH) and does not incorporate facility capacity constraints. A real-world operational model would need to be more dynamic, accounting for situations where a full TSS would require rerouting materials to the next available site. Second, the model does not include explicit costs, such as land, labor, or fuel; it uses tonne-kilometers as a proxy for transport effort and cost. Third, it assumes constant vehicle types and capacities and does not model the complexities of fleet management. Finally, the model is static, meaning it does not account for real-time variables like traffic congestion or temporal fluctuations in material supply and demand beyond the aggregated annual data. These assumptions were appropriate for a strategic-level spatial analysis but would need to be refined for a detailed operational or tactical simulation.

Moreover, the candidate pool for Temporary Storage Sites (TSS) was constrained by an initial suitability analysis that filtered for locations within a 3-kilometer service area of project clusters and main hubs. As highlighted during expert consultations (Expert 3, Appendix C.3), this approach may have prematurely excluded potentially optimal locations that fell just outside these zones, thereby limiting the solution space for the subsequent optimization algorithm.

Data

The research is constrained by the nature of the available data. The tonnage calculations were based on average values for material thickness and density, which may vary in practice. The road network and land use information were sourced from OpenStreetMap (OSM), which, while an excellent open resource, may have inaccuracies compared to official cadastral data. Furthermore, the project data, while comprehensive, lacked the granularity to model daily or weekly variations.

The optimization approach also has limitations. The Greedy Heuristic algorithm developed for this study finds a near-optimal, not a globally optimal, solution. Its primary goal was to serve the spatial-analytical aims of the thesis, not to perform full-scale mathematical optimization. As recommended in the discussion, a real-world implementation should leverage more advanced methods like mixed-integer programming to achieve guaranteed optimality.

Scope

The scope of this research was deliberately focused to ensure depth of analysis. It concentrated on a specific set of reusable materials (concrete tiles and bricks) and did not include the full spectrum of construction and demolition waste. Additionally, the study is geographically specific to the case of Amsterdam. While the DSRM framework and the strategic principles derived are designed to be transferable, the specific network of 5 CCHs and 6 TSSs is a context-dependent solution. Applying this framework to other cities would require re-calibrating the model with local data and constraints.

6.3. Recommendations for Future Research

The limitations identified in this study suggest several important directions for future research to build on the strategic framework developed here:

Dynamic Operational Simulation Model

Future work could create a more dynamic simulation that includes facility capacity constraints, models daily or weekly demand fluctuations, integrates real-time traffic data, and considers different types of vehicles and operating rules. Agent-based or discrete-event simulation models would be suitable for this more detailed analysis.

Comprehensive Economic Analysis

While this thesis used tonne-kilometers as a cost proxy, future research could conduct a full cost-benefit analysis. This would include all relevant costs (such as land, operations, labor, and fuel) and benefits (such as reduced transport distances, emissions, and improved productivity).

Expanding the Scope:

The model could be broadened to include other major construction and demolition waste streams, such as asphalt, wood, or metals, for a more complete city-wide circularity assessment. Applying the framework to cities with different geographies and policies could also test the transferability of the strategic principles.

Advanced Optimization

Advancing from near-optimal to globally optimal solutions could require the use of advanced optimization techniques, such as mixed-integer programming or metaheuristics, to achieve maximum efficiency and robustness in network design.

Governance and Business Models

Further research could investigate governance structures and business models, including public-private partnerships and contractor incentives, to support effective real-world implementation.

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A
Compounded Travel Distance

The Hub-and-Spoke configuration used in this research involves a two-stage transportation process, with the total system distance calculated by summing distances traveled in two distinct legs: Leg 1 (Source Collection) and Leg 2 (Consolidated Transport). Figure A.1 are given as an example to demonstrate the calculation.

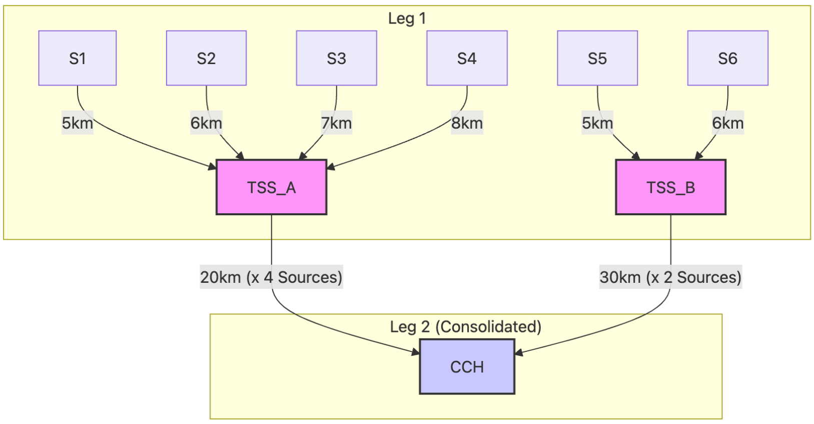


Figure A.1: Example calculation of two-leg distances in the hub-and-spoke model.

Leg 1: Source Collection (Source $\rightarrow$ TSS)

This leg involves collecting materials from individual source locations and delivering them to the nearest designated TSS. The total distance is calculated by summing the individual shortest path distances from each source to its assigned TSS.

Let:

- $S_A = \{S_1, S_2, S_3, S_4\}$: sources assigned to TSS_A
- $S_B = \{S_5, S_6\}$: sources assigned to TSS_B
- d_{i,TSS_A} be the distance from source $i \in S_A$ to TSS_A
- d_{j,TSS_B} be the distance from source $j \in S_B$ to TSS_B

Then, the total distance for Leg 1 is given by:

$$\text{Total Leg 1 Distance} = \sum_{i \in S_A} d_{i,TSS_A} + \sum_{j \in S_B} d_{j,TSS_B}$$

For given example:

- If S_1 to S_4 are assigned to TSS_A with distances of 5 km, 6 km, 7 km, and 8 km respectively, then their total is $5+6+7+8=26$ km.
- If S_5 and S_6 are assigned to TSS_B with distances of 5 km and 6 km, their total is $5+6=11$ km.

Thus, the total Leg 1 distance equals $26+11=37$ km.

Leg 2: Consolidated Transport (TSS → CCH)

The second leg involves transporting aggregated materials from the TSS to the CCH. This transport leg requires weighting the travel distances by the number of source trips consolidated at each TSS.

Let:

- T be the set of all TSS locations.
- n_t be the number of sources assigned to TSS $t \in T$.
- $d_{t,CCH}$ be the distance from TSS t to the CCH.

Then, the total weighted distance for Leg 2 is given by:

$$\text{Total Leg 2 Distance} = \sum_{t \in T} n_t \cdot d_{t,CCH}$$

For given example:

- If TSS_A consolidates material from 4 sources and has a distance of 20 km to the CCH, the weighted distance is $4 \times 20 = 80$ km.
- If TSS_B consolidates material from 2 sources and has a distance of 30 km to the CCH, the weighted distance is $2 \times 30 = 60$ km.

Thus, the total weighted distance for Leg 2 equals $80+60=140$ km.

Total System Distance (Hub-and-Spoke) The overall transport distance for the model combines both legs:

- Leg 1: 37 km
- Weighted Leg 2: 140 km

Thus, the total system distance is:

$$\text{Total System Distance} = 37 \text{ km} + 140 \text{ km} = \boxed{177 \text{ km}}$$

This calculation accurately captures the true transport effort, considering both collection and consolidation legs.

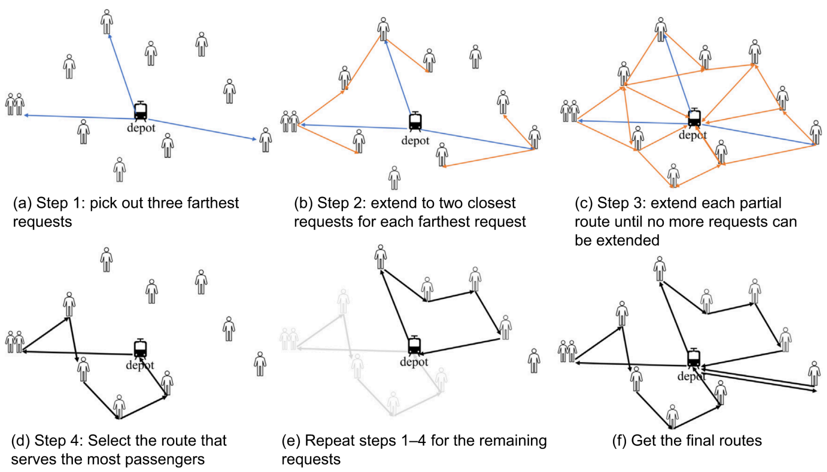
B

Greedy Heuristic Algorithm

B.1. Conceptual Principle

The selection of Temporary Storage Sites (TSS) in this research employed a Greedy Heuristic algorithm with an iterative best addition strategy (as detailed in Methodology Section B.2).

This illustrative example was taken from He et al. (2023), in which they demonstrated a greedy algorithm based on the solution's characteristic of the first-mile ride-sharing to the intercity transportation hub (FMRITH) problem. While the specific mechanics of selecting facility locations differ from constructing vehicle routes, the underlying principle of making locally optimal choices at each step to build a good overall solution is common to many greedy heuristics. Figure B.1 below illustrates a conceptual example of a greedy heuristic applied to a route-building problem, which helps to visualize this iterative, step-by-step decision-making process.



(a) Step 1: pick out three farthest requests

(b) Step 2: extend to two closest requests for each farthest request

(c) Step 3: extend each partial route until no more requests can be extended

(d) Step 4: Select the route that serves the most passengers

(e) Repeat steps 1–4 for the remaining requests

(f) Get the final routes

Figure B.1: Conceptual illustration of a Greedy Heuristic for route construction (He et al., 2023)

This diagram could be understood as follows in relation to the greedy principle:

- **(a)**: The process often starts by identifying initial key elements or considering a subset of possibilities. In the diagram, "three farthest requests" are chosen. In the TSS selection, each iteration considers all remaining unselected candidate TSS as potential next additions.
- **(b) & (c)**: Based on the initial elements, options are explored or expanded. The diagram shows extending routes to "two closest requests" and then further "until no more requests can be extended." In the TSS selection, for each candidate TSS being considered for addition, the algorithm simulates the entire network flow and evaluates its performance based on the hierarchical

criteria (tonnage captured, TSS-CCH distance, total tonne-kilometers). This evaluation is more complex than simply finding the ”closest” next stop but follows the same idea of assessing potential additions.

- **(d)**: A decision is made based on which option best meets the current objective. The diagram shows ”Select the route that serves the most passengers.” In the TSS selection, the candidate TSS that results in the best outcome according to the hierarchical criteria (first maximizing tonnage via TSS, then minimizing TSS-CCH distance, then minimizing total tkm) is chosen as the ”best addition” for that iteration.
- **(e)**: The process is repeated for the remaining unselected elements. The diagram shows ”Repeat steps 1-4 for the remaining requests.” In the TSS selection, once a TSS is chosen and added to the ”active set,” the algorithm proceeds to the next iteration, again considering all remaining unselected TSS candidates for addition to the newly expanded active set.
- **(f)**: The process continues until a stopping condition is met (e.g., all requests served, or a target number of routes/facilities achieved), resulting in the final set of routes or, in the case of this research, the final selected set of TSS locations.

While Figure B.1 illustrates route construction, the core greedy heuristic principle is similar to the TSS selection process.

1. Begin with no TSS selected (or a predefined CCH network).
2. In each iteration, evaluate every potential but currently unselected TSS as if it were added to the network. This involves recalculating material flows and the performance metrics (tonnage, distances, tkm).
3. Select the single candidate TSS that provides the ”best” improvement according to the hierarchical criteria (e.g., attracts the most additional tonnage, or if tied, has the best TSS-CCH distance, or if still tied, results in the best tkm).
4. Add this chosen TSS to the set of ”active” TSS locations. Repeat steps 2 and 3 with the remaining unselected TSS candidates until the desired number of TSS is reached or no further beneficial additions can be made.

This illustration, therefore, serves to visually illustrate the general iterative and locally-optimal decision-making nature inherent in the greedy heuristic approach employed for identifying the strategic set of TSS locations in this study.

B.2. Model Implementation

The iterative best addition process involved several key operational steps. First, a routable graph was constructed from the available road network data, and the grid of potential candidate TSS locations was mapped to the nearest nodes on this network. Shortest path distances for all relevant journey segments (Origin-to-TSS, Origin-to-CCH, and TSS-to-CCH) were then precomputed to facilitate efficient evaluation during the iterative process.

A core component of evaluating network performance within the hub-and-spoke model is the accurate calculation of total transport distances. This involves summing distances traveled in two distinct legs: Leg 1 (Source Collection), which captures the initial movement of materials from their origin to either a TSS or directly to a CCH, and Leg 2 (Consolidated Transport), which represents the movement of aggregated materials from a TSS to a CCH. Crucially, the distance for Leg 2 is weighted to reflect the number of source trips consolidated at each TSS, ensuring an accurate representation of the total transport effort. The overall system distance, which is the sum of the total Leg 1 distance and the total weighted Leg 2 distance, forms the basis for calculating tonne-kilometers. A detailed explanation of this two-leg distance calculation methodology, including illustrative examples, is provided in Appendix A.

The core of the algorithm was an iterative selection loop, which proceeded from selecting the first TSS up to the user-defined maximum. In each iteration of this loop:

1. Every unselected candidate TSS was temporarily considered for addition to the set of currently active TSS.
2. For each such temporary network configuration (active TSS + one new candidate TSS), material flows were re-simulated from all origins according to the defined first-leg routing rule, utilizing the precomputed shortest path distances and the two-leg distance calculation framework referenced above.
3. The performance of this temporary network configuration was then evaluated based on a set of hierarchical criteria (see Subsection B.3), with a key component of this evaluation being the calculation of the total system tonne-kilometers, derived from the total system distances.
4. The unselected candidate TSS that yielded the most significant improvement (or best performance) according to these hierarchical criteria was then permanently added to the set of active TSS for that iteration. This newly selected TSS then remained active for all subsequent iterations.

This iterative process continued until the specified number of TSS were chosen, with each selected TSS representing the best possible addition to the network at that particular stage, given the sites already incorporated.

B.3. Model Criteria

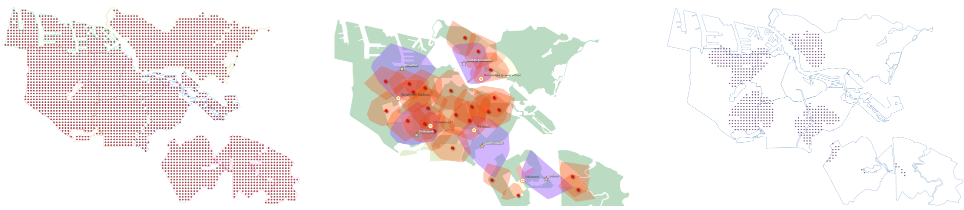
Recognizing the complexities regarding the metrics (as discussed in Section 3.4.2, the greedy heuristic for TSS selection in this research did not solely pursue the minimization of tkm. Instead, it aimed to strategically balance three interconnected, and sometimes competing, objectives in a hierarchical manner:

1. First, maximizing the amount of tonnage consolidated at TSS was prioritized to ensure that selected sites actively capture and consolidate a significant volume of materials.
2. Second, minimizing the distance between each TSS and its designated CCH aimed to improve the efficiency of the second-leg (consolidated) transportation.
3. Third, minimizing the total system tonne-kilometers served as a crucial safeguard against excessive travel distances, particularly as more TSS locations become operational, thereby maintaining the system's overall economic and environmental viability.

These objectives represent a structured trade-off, guiding the heuristic through iterative phases where initial iterations might prioritize maximizing TSS usage, while later stages progressively refine the network for enhanced efficiency. It is acknowledged, however, that a comprehensive evaluation would ideally consider additional metrics beyond tonne-kilometers, such as specific operational costs or detailed carbon emissions, which could be subjects for future model enhancements.

B.4. Model Inputs

The execution of the greedy heuristic algorithm, as detailed previously, relied on a set of specific spatial and attribute datasets:



(a) *Full 250x250m grid* **(b)** *Service area* **(c)** *Selected candidate grid*

Figure B.2: Generation of candidate grid points for TSS siting.

- **Material origins:** represented by point features derived from the polygon centroid of road maintenance projects. Each origin point was associated with a unique identifier and, crucially, an estimated tonnage of recoverable materials.

- **CCH destinations:** the selected candidate CCH locations from Phase 1 used as the final destinations for materials. Materials could flow either directly from an origin to a CCH or be routed via an intermediate TSS to a CCH.
- **Road network:** Amsterdam road network sourced from OpenStreetMap.
- **Candidate grid points:** grid represented a potential site for establishing a TSS generated with a 250x250 meter spacing (B.2c). To ensure computational efficiency and focus the search on strategically relevant zones, this grid was spatially clipped to areas within the anticipated service regions (3 km) of both the road maintenance project clusters (material sources) and the selected CCH locations (Figure B.2b). The
- **Number of TSS:** operational parameter, the maximum number of TSS to be selected by the algorithm, was defined by the user. For the simulations conducted in this research, this parameter was set to allow for the iterative selection of up to 20 TSS locations. This enabled the observation of incremental performance changes and the identification of diminishing returns as more TSS were added to the network.

B.5. Model Output

The execution of the greedy heuristic algorithm, as detailed in the preceding sections, yielded several key outputs that directly informed subsequent stages of the research. These outputs provide both a spatial configuration of the selected Temporary Storage Sites (TSS) and quantitative data on the network's performance during their iterative selection.

The primary spatial output was an ordered set of selected TSS locations, pinpointed from the pool of candidate grid points. The algorithm generated a ranked list, with each TSS selected sequentially based on its incremental contribution to network performance as evaluated against the predefined hierarchical criteria at each step. This ordered set represents the algorithmically determined optimal sequence for adding TSS to the network, up to the specified maximum number. The spatial distribution of these selected TSS in relation to the established CCH locations is illustrated in Figure B.3.

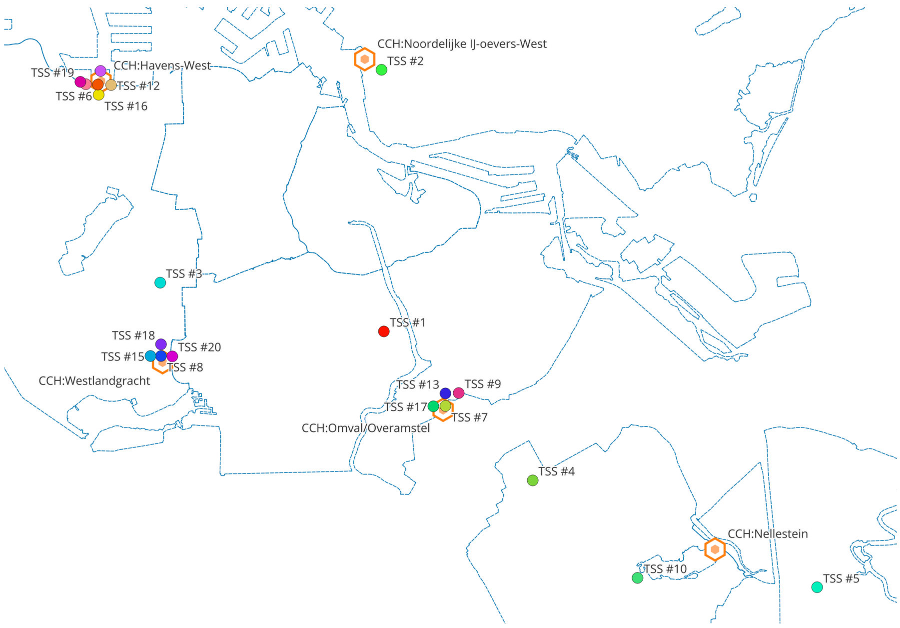


Figure B.3: Spatial distribution of CCHs and algorithmically selected TSS locations.

In parallel with the spatial selection of TSS, the process produced a comprehensive record of iterative performance metrics. For each step in which a TSS was added to the network (from the first up to the maximum considered), key indicators of network performance were calculated and documented.

Table B.1: Greedy Algorithm results for TSS locations.

TSS Amount (#)	Projects Served (#)	Total Tonnage (t)	Δ Tonnage (%)	Total Distance (km)	Δ Distance (%)	Total Tonne-km (t-km)	Δ Tonne-km (%)
0	0	0	-	1,232.72	-	1,143,407	-
1	110	96,608	-	1,349.27	+9.45	1,277,107	+11.69
2	186	179,175	+85.47	1,361.54	+0.91	1,292,647	+1.22
3	229	238,608	+33.17	1,393.60	+2.35	1,347,815	+4.27
4	246	278,605	+16.76	1,444.81	+3.67	1,480,857	+9.87
5	269	300,244	+7.77	1,450.58	+0.40	1,484,711	+0.26
6	291	310,727	+3.49	1,445.32	-0.36	1,481,114	-0.24
7	293	315,914	+1.67	1,445.44	+0.01	1,481,398	+0.02
8	300	319,743	+1.21	1,445.78	+0.02	1,481,581	+0.01
9	303	322,944	+1.00	1,447.96	+0.15	1,483,917	+0.16
10	305	323,124	+0.06	1,431.68	-1.12	1,431,259	-3.55
11	305	323,124	+0.00	1,431.68	+0.00	1,431,259	+0.00
12	305	323,124	+0.00	1,429.70	-0.14	1,430,655	-0.04
13	305	323,124	+0.00	1,422.34	-0.51	1,405,353	-1.77
14	305	323,124	+0.00	1,422.34	+0.00	1,405,353	+0.00
15	305	323,124	+0.00	1,422.34	+0.00	1,405,353	+0.00
16	305	323,124	+0.00	1,422.46	+0.01	1,401,632	-0.26
17	305	323,124	+0.00	1,422.37	-0.01	1,401,396	-0.02
18	305	323,124	+0.00	1,409.13	-0.93	1,387,206	-1.01
19	305	323,124	+0.00	1,409.13	+0.00	1,387,206	+0.00
20	305	323,124	+0.00	1,407.81	-0.09	1,384,433	-0.20

Note: *Slight discrepancies (approximately 5%) may occur due to rounding differences and compounding path calculations. As a result, the output from the algorithm is used primarily for comparison, while manually calculated results are used for final network performance evaluation.*

C

Interview Summary

C.1. Interview Summary A

Interview with Expert 1, June 17, 2025

An expert in strategic insights, policy, governance, and circularity, referred here as Expert 1 (E1), was interviewed on June 17, 2025. E1 is closely involved with the Amsterdam municipality in efforts to enhance circular practices in road maintenance. The conversation focused on evaluating strategically located circular construction hubs to improve transport efficiency and circularity efforts in road maintenance. Key findings from the interview are summarized below.

Existing Circular Construction Hubs

The two most important existing hubs are Stadswerken Theemsweg and Circulaire hub Sluispolderweg. Their establishment resulted not from strategic selection but from first-mover initiatives. Beentjes, one of the large framework contractors, was the only one to align with the municipality's ambition to develop circular infrastructure. The municipality is now attempting to take a more strategic approach to hub placement, although this is complicated by the availability and high cost of space in Amsterdam.

The municipality has implemented substantial policy changes to control the material flow. All materials now remain under municipal ownership, and every project must send materials to either Beentjes (Sluispolderweg) or Stadswerken (Sluispolderweg). A municipal intranet, described by E1 as a 'low-tech version of Amazon for reusable bricks and reusable things', has been developed to provide a digital overview of materials in storage at Stadswerken depots.

Role of Temporary Storage Sites

Temporary storage sites (TSS), or smaller hubs, could support the larger Circular Construction Hubs (CCH). Initially assumed to be buffer zones for main hubs, E1 emphasized that their actual value lies in serving as distribution points for processed materials. The circular hubs would handle processing, while TSS would store clean pallets of reusable materials until needed for future projects. This setup allows the circular hubs to focus on processing with high throughput. Temporary hubs can also help manage timing discrepancies in construction projects by acting as planning buffers.

Hubs Governance

Governance should be a collaborative effort between the municipality and contractors. The municipality provides the overarching vision, while contractors are offered opportunities to engage with and shape the transition. Contractor involvement in hub development may enhance their prospects for future contracts.

A current challenge is the absence of a contract structure for circular hubs that ensures long-term planning security for contractors. E1 suggests that a dedicated policy framework could incentivize contractors to provide their own storage spaces. Nevertheless, municipal sites remain crucial for storing materials that are not readily reusable. Collaboration with contractors is seen as a complementary, rather than a replacement, strategy.

Transport Efficiency and Circularity

Improving transport efficiency is vital to the financial viability of circular road maintenance. While transportation's environmental impact is less significant than the embodied impacts of material manufacturing, its cost is a major barrier. For example, broken bricks are not sent back to factories for recycling due to high transport costs. Reducing these costs is essential for making circular practices more attractive to stakeholders.

Next Steps for a Coordinated System

To move from a fragmented system to a more strategic and coordinated one, several steps are necessary:

- **Scale up capacity:** Current hub infrastructure is inadequate. Facilities like Beentjes (Sluispolderweg) must increase capacity from handling tens of thousands to hundreds of thousands of square meters.
- **Expand to other materials:** Present efforts are focused mainly on bricks. Circular solutions must be developed for other materials, particularly *betontegels* (concrete tiles), the most common paving material in the city.
- **Develop a distribution system:** As capacity grows, more local storage hubs will be required to facilitate efficient material distribution to projects.
- **Implement policy and accountability:** The municipality must offer policy certainty to reduce risks for contractors and encourage infrastructure investment. This includes requirements not only for outgoing reuse rates but also for incoming reuse in new projects to stimulate demand for recycled materials.

C.2. Interview Summary B

Interview with Expert 2, June 26, 2025

The interview was conducted with Expert 2 (E2), a Senior Advisor on Sustainable Urban Development for the City of Amsterdam. With a professional background in architecture and urban planning, E2's current role focuses on the circular built environment. He functions as a critical link between citywide policy makers, who set ambitious circularity goals such as using 50% circular materials, and the urban planners who design public spaces. His work involves translating these high level strategies into practical, achievable actions within specific projects, particularly in the southeast of Amsterdam.

The Challenge of Spatial Scale and Land Availability

A crucial point raised by E2 was a reality check on the spatial scale required for such an initiative. He provided a critical calculation from the city's own assessments: to achieve the ambitious goal of reusing 85% of bricks from pavement, an estimated 50,000 square meters of storage space would be needed. This figure means the city would require five of the 1-hectare CCHs proposed just to handle bricks, highlighting a massive demand for space.

This requirement directly conflicts with the extreme scarcity of land in Amsterdam. E2 emphasized that finding and designating a 1-hectare plot for this purpose within the city is "very, very big" and almost impossible. He suggested that a more feasible or "reasonable" size for a plot that could be temporarily designated within an urban development is closer to 5,000 or 7,000 square meters. Furthermore, storage is considered a "very low form of use" that does not generate revenue, putting it in direct competition with high-value functions like housing, offices, and energy infrastructure that command priority for any available land.

Critique of Logistical Models and Complexity

E2 strongly advised against the complexity of the Hub-and-Spoke model, particularly the step of moving materials from a temporary site to a main hub. He stated, "I ideally I would would try to avoid going from hub to hub." He explained that within a large organization like the city, every transfer point introduces a significant risk of system failure, where materials can be lost, damaged, or their chain of custody becomes unclear. The preferred approach is to prioritize simplicity, where a critical assessment is made at the source of the material to decide immediately if it goes directly to a local temporary site for short term use or to a main CCH for long term storage and processing.

Following this, E2 advocated for embracing just-in-time principles to minimize storage altogether. The ideal system would combine processing and storage and facilitate the direct movement of materials from their source to the next site where they will be used. He argued that any intermediate step is a "complicating factor" that makes the entire process "very costly." He also dismissed the idea that temporary hubs would be useful as transition points for the upcoming 2028 zero-emission zone. He reasoned that the entire city and its vehicle fleet will transition over the next five to ten years anyway. Because the hubs are planned for a 25-year lifespan, their location should be based on long term logistical efficiency rather than a temporary vehicle transition period.

Practical Recommendations for Facility Configuration

For practical implementation, E2 recommended a strategy of hyper-local, short term storage for needs under three months, suggesting that materials should be stored within the neighborhood or project area itself. He provided examples of temporary, fenced off storage areas located on plots slated for future development. He also suggested that the model should incorporate more temporary sites than currently proposed, preferring a distributed network of smaller spaces over a few sites clustered near the main CCHs. E2 further recommended consolidating city functions by pointing to an area where a municipal garbage facility, a vehicle depot, and offices were co-located, suggesting this area could be developed into a single, efficient circular hub.

The expert also stressed the need to better define the requirements for a "temporary storage site." He noted that there is a critical operational difference between simply using a few open parking spots versus establishing a guarded, fenced area with a proper floor capable of handling heavy materials. These specifications are essential for practical implementation and risk management.

The Socio-Economic Dimension of Circularity

E2 made a powerful point about the importance of making circularity visible to the public. He argued that when circular hubs are visible within city development areas, people can see materials being stored and reused, which helps the concept become "part of the DNA of the city." Conversely, if all recycling and reuse activities are hidden on the outskirts, "nobody gets circularity in their head," and it remains an abstract and distant idea.

Finally, E2 highlighted the human and organizational barriers that must be overcome. For circularity to succeed, processes must be clear and predictable. Stakeholders often hesitate when there is ambiguity concerning who is responsible for materials, whether a site is secure, and how long materials can be stored. This lack of clarity leads to inaction and causes people to default to traditional, linear disposal methods, ultimately undermining the entire circular effort.

Conclusion

The interview clearly highlights the main challenge in achieving urban circularity: the need for large, efficient spaces for processing and storage is at odds with the severe shortage of land in a crowded city. According to E2, there is no single perfect model that can solve this issue. Instead, success depends on finding a careful and strategic balance. This balance should involve a few medium-sized, permanent Circular Construction Hubs (CCHs) that are realistically sized, along with a broad network of smaller, highly local temporary storage sites. The overall logistical system should focus on simplicity and direct movement of materials to reduce complexity and costs. Most importantly, these operations need to be visible within the city so that the public can see circularity in action, which is essential for encouraging the cultural and behavioral changes needed for a circular economy to succeed.

C.3. Interview Summary C

Interview with Expert 3, July 8, 2025

Expert 3 (E3) is a researcher with expertise in applying data science and spatial analysis to the circular economy. Her work focuses on the logistics of construction materials, the optimization of circular hub networks, and the classification of different hub typologies.

The interview focused on the methodology and results of this thesis. E3 provided critical feedback and insights on the approach used to locate both main and temporary circular construction hubs.

Temporary Sites Candidates Selection

The methodology for identifying candidate locations for temporary storage sites (TSS) involved selecting the geographic overlap between project clusters and a 3-kilometer service area around the main hubs. However, E3 was not fully convinced by this approach and offered a critical perspective. She argued that this method unnecessarily limited the solution space, noting that an optimal location for a temporary hub might exist just outside the defined 3-kilometer radius or between two main hub service areas. Such locations, she suggested, could significantly improve overall network efficiency. Furthermore, E3 considered the 3-kilometer service area to be a somewhat arbitrary cutoff, reasoning that transport efficiency does not suddenly drop off beyond this specific distance.

As an alternative, E3 proposed applying a broader, less strict version of the site suitability analysis to the entire Amsterdam area to identify candidate locations for temporary hubs. This would generate a larger and more comprehensive set of potential sites for the optimization algorithm to evaluate, thereby making the final results more robust by demonstrating that all possible solutions were considered. In response, it was explained that the rationale for the original filtering method was to keep the transport effort metric low by ensuring temporary sites were close to both main hubs and project clusters, while also accounting for real-world constraints, such as the difficulty of placing storage sites in busy or protected areas.

Greedy Algorithm and Optimization Results

The discussion then turned to the greedy algorithm used for locating temporary hubs, which was designed to prioritize three main objectives: serving the largest project tonnage, ensuring proximity to a main hub, and keeping transport distances low. E3 expressed particular interest in the outcomes of the 20 optimization scenarios, which tested configurations ranging from one to twenty temporary hubs. She found the identification of an ”elbow point,” or a point of diminishing returns, around ten hubs to be especially insightful and valuable. E3 agreed that the most significant finding was that the optimized network could achieve substantial transport savings with a relatively small number of hubs. She considered this result to be the most convincing aspect of the research and highlighted its potential value for municipal decision-makers.

General Discussion on Circular Hubs

The general discussion on circular hubs and logistics covered several important concepts raised by E3. She introduced the idea of ”no-regret” solutions, a concept from her own research on timber hubs. By overlaying the results of 150 different scenarios, her team was able to identify specific industrial sites that were consistently chosen as optimal hub locations regardless of the scenario. E3 suggested that pinpointing such robustly beneficial locations is highly valuable, as it gives municipalities confidence to reserve these sites for future circular activities.

Regarding the function of temporary hubs, E3 explained that both consolidating raw materials before processing and consolidating processed materials for distribution are valid and useful purposes. The fundamental goal, in her view, is to improve logistical efficiency, such as by reducing the number of half-empty truck journeys.

The conversation also addressed different types of hubs. E3 distinguished between large-scale industrial hubs, like those analyzed in this thesis, and smaller, customer-facing craft hubs which benefit from being located closer to residential areas. On the topic of hub size, it was noted that a 1-hectare parameter was used in this research. E3 clarified that the sizing figures in her own publications were sourced directly from municipal documents and emphasized that municipalities themselves are best positioned to determine the ideal land size requirements.

D

Supplementary Insight

Personal Communication Summary: Industry Professional

Discussions with Expert 4, April 28, 2025

The following key points were synthesized from notes taken during an informal professional discussion in April 2025 with an experienced contractor in the Amsterdam road maintenance sector. This was not a formal, recorded interview, but rather an unstructured conversation aimed at gathering practical perspectives. In addition to the discussion, the expert also provided written responses to several follow-up questions via email, which were used to supplement the insights from the conversation. To maintain confidentiality and reflect the informal nature of these exchanges, the individual is referred to as Expert 4 (E4) throughout this thesis.

On-Site Handling and Sorting

The standard approach for removed paving materials depends on the scale and type of maintenance, categorized as large (*groot onderhoud*), small (*klein onderhoud*), or replacement (*vervanging*). In most cases, materials are transported directly to waste processors, with reuse being rare except in limited small-scale projects. Although visual inspections and informal sorting by material type and quality are performed on-site, standardized national protocols are lacking.

Reuse decisions are typically defined in the project contract (commonly a *bestek*), which outlines whether materials must be transported to certified processors or can be reused. Often, even reusable materials are discarded to meet client expectations for durability and avoid future maintenance. Time constraints and cost priorities often lead to acceptance of material breakage during removal.

Temporary Storage Site

Temporary material storage near construction sites is highly context-dependent. While projects in rural areas (e.g., grasslands in Friesland) can accommodate on-site storage, dense urban areas like Amsterdam often lack space. Permits for public space storage can be obtained, but require early planning and client approval. Risks such as theft, weather exposure, and urban disturbance are acknowledged but not centrally regulated. The APV (General Local Regulation) is reportedly not strictly enforced in practice.

Transport Logistics

Transport is typically organized by the contractor, either through in-house resources or third-party services. Larger trucks (30T) or smaller vehicles (9–12T) are used depending on material volume. Scheduling of transport varies by project and hinges on factors like truck availability, waste facility capacity, and project planning. Return logistics (reverse transport) is rarely optimized due to scheduling and sequencing limitations. Final destinations and transport routes are determined by the client, material type, and its condition.

Broader Materials Flow and Planning

All public road material movements must be documented, including origin, destination, material type, and ownership. Intermediate storage or sorting hubs exist primarily where contractors or clients operate private depots, rather than through a city-managed hub network. Municipalities like Amsterdam and Utrecht are promoting reuse through internal goals and draft guidelines, but regulatory mechanisms remain limited.

Reflections and Constraints

A critical challenge is client decision-making. Contractors observe that clients often set circular goals but retreat once they see the financial implications. There is also a persistent lack of awareness among clients about the quality and performance of recycled materials (e.g., reused concrete tiles).

According to the contractor, handling practices are already logistically optimized, with cost efficiency driving most decisions. Reducing transport distances remains a key opportunity area, as logistics are the most significant constraint after client preferences.

E

Greedy Heuristic Code

The full source code and documentation required to reproduce the analysis in this thesis are available on GitHub repository.