# Measuring Renovation Waste Flows of Buildings in the Netherlands

MSc Industrial Ecology: Thesis Research Project

*Skip (3 m$^3$) found in Leiden*

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**Date:** 25/9/2024

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# Acknowledgments

I would like to extend my gratitude to everyone who supported me throughout this thesis journey.

First, a big thank you to Tomer Fishman for his guidance and insightful feedback. Your expertise and support kept me on track, and I truly appreciate the time and effort you dedicated to helping me improve my work. Thank you to John Heintz, who made sure I kept an eye out to the real world while working with a large dataset. And a special thank you to Catrin Böcher who was available for weekly meetings which helped me stay on track and through the struggles that come with a master's thesis.

I want to thank my family for supporting me throughout my studies, both mentally and financially. My mother helped me take my mind off the thesis during our work at the yarn shop. My father provided me with news articles on the developments of the construction sector and local circular economy initiatives, and the calls with my sisters helped me relax and stay motivated.

A special thanks to Charlotte for the brainstorming sessions and much-needed breaks at the Hortus Botanicus. It was a pleasure getting to know you through our studies, and I'm grateful for the positivity and fresh perspectives you brought. I look forward to a long friendship based on shared struggles and rugby talk.

I also want to recognize my friends Esther, Sofie, and Michaja. Our shared study sessions were filled with support, productivity, tears, and laughter, for which I am deeply thankful. You paved the way for me, which probably prevented a substantial number of struggles.

Finally, I want to express my appreciation to my housemate Marchien, with whom I spent late nights at the Civil Engineering faculty, who not only helped proofread my work but also made sure I was well-fed during the more intense periods. Your support, both practical and emotional, made a huge difference.

This thesis wouldn't have been possible without all of you, and I am deeply grateful for your presence in my life.

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# Abstract

The construction sector, known for its extensive use of building materials, significantly contributes to environmental degradation, resource depletion, and waste management challenges. While much attention has been given to creating circular systems in demolition, renovation processes—occurring more frequently due to varying lifespans of building elements—remain underexplored. Understanding the material output from renovation projects across different building types and their potential for reuse and recycling is crucial.

This thesis introduces a novel approach to calculating renovation and transformation waste, drawing on existing literature related to skip use for material intensity (MI) calculations for demolition and waste quantification. Renovations are defined as improving a building to enhance the physical conditions and functional performance. Transformations are similar to renovations but include a change of use of the building. Data on renovation and transformation projects were acquired to calculate the amount of waste generated as well as the renovation and transformation material intensities (r,tMIs) of different building types and for different construction years. The r,tMIs were calculated by dividing the mass of each material per project by the floor area of that project. The r,tMIs were then grouped by building type and construction year. The materials examined include Undifferentiated, Gypsum, Wood, Synthetic material, Paper/cardboard, and Aggregates. The building types are classified as detached houses, row houses, apartments, educational buildings, health facilities, offices, and 'other', with construction years grouped into Before-1945, 1945-1970, 1970-2000, 2000 and later, and Year unknown. The 358 projects are dispersed across the Netherlands and took place between January 2021 and May 2024.

It was found that the Undifferentiated waste stream constitutes a large portion of both renovation and transformation waste. Among renovation projects, apartments represent a significant portion, while transformation projects are limited to educational buildings, offices, and 'other' categories. Transformation projects tend to have higher tMI values compared to renovation rMIs. Undifferentiated and Aggregates are consistently present across all building types, whereas Gypsum and Synthetic materials are less common in number and mass. Additionally, a trend of decreasing tMI values for newer buildings was observed in transformation projects, a pattern not evident in renovation projects.

These insights lay the groundwork for a deeper understanding of material flows in renovation and transformation practices, serving as a strong foundation for future research. The findings can be used by renovation companies and contractors to estimate the amount of renovation waste from future projects by multiplying the r,tMIs with the specific floor area of that project. The findings can also be used by waste treatment companies to increase the efficiency of waste collection, transport, and treatment.

# 1. Introduction

This thesis focuses on quantifying and characterizing renovation waste in the Dutch building sector. The primary objective is to calculate the amount and identify the type of waste generated during renovation projects across different building types. While substantial research has been conducted on construction and demolition waste of demolitions, there is a notable knowledge gap in understanding the waste flows associated with renovation (Huuhka et al., 2023; Vilches et al., 2017). This gap limits the ability to optimize material reuse and recycling within the framework of a circular economy, as information on the quantity and type of waste from renovation is needed to have a chance at reusing the waste as resource again (European Commission, 2020). This circular approach helps reduce the demand for primary resources and with that the emissions that are connected to global warming (United Nations, 2024). Therefore, this study aims to fill this research gap by investigating containers placed on the street during renovation and analyzing data from companies on skips used during renovation projects. The insights gained from this research could inform the construction sector and local governments in developing sustainable building practices and waste management strategies.

## 1.1 Research Motivation

The construction sector, characterized by its substantial utilization of building materials and transport activities throughout production, construction, renovation, and demolition processes, is a prominent contributor to environmental degradation, resource depletion, and waste management issues. This is not surprising, considering it accounts for approximately half of the global material demand (United Nations Environment Programme & International Resource Panel, 2019). In combination with the expected population growth and urbanization trends, the material demand continues to increase (Fishman et al., 2016; Wiedenhofer et al., 2019).

In recent decades, the typical approach to creating new products or buildings has been to rely on raw materials extracted from the earth. After these materials serve their purpose and reach the end of their life cycle, they are often discarded as waste, without considering their potential for reuse or recycling (Raworth, 2017). This linear system of material use has led to extensive resource extraction causing a severe waste issue. The levels of material demand of the Netherlands observed in 2019 are 2.5 times higher compared to 2016 (PBL Netherlands Environmental Assessment Agency, 2023). This intense use of primary materials can be mitigated, by transitioning to the use of secondary materials, moving towards a circular economy (European Parliament and Council Directive, 2018; Gontia et al., 2018; Mohammadiziazi & Bilec, 2023).

According to CBS (Statistics Netherlands), the Dutch construction sector reports a recycling rate exceeding 99% (CBS, 2019). However, this figure encompasses the entire construction sector, including road construction, which frequently downcycle the demolition material from buildings. When focusing specifically on the building sector, it reveals a lower recycling rate of only 11.4% in 2016, however, the materials are recycled into products of a similar value to the original product (CBS, 2019). With the construction sector generating the most waste in the Netherlands, this raises concerns (CBS, 2019) .

Next to the material issue, the Netherlands is struggling with a housing shortage. According to the Ministry of the Interior and Kingdom Relations (BZK) in collaboration with ABF Research, there are 8.270 million households but only 8.125 million dwellings in the Netherlands. This means new dwellings are needed (BZK, 2024). Therefore, extending the lifetime of the current buildings through regular maintenance and performance upgrades helps fight the housing shortage as well.

According to Metabolic (2020) and Wiedenhofer et al. (2015), renovation processes of building elements happen more often than construction and deconstruction of buildings because of the different lifetimes. This can be explained by the difference in the lifetime of the different layers of the building, thought of by Frank Duffy, and elaborated by Steward Brand (1994) (see figure 1.1). The Skin includes all the exterior surfaces, which are changed roughly every 20 years, and is also where you would improve the insulation. The Services layer includes the elements that are actively used during the use-phase of the building. The Space Plan is the layer consisting of the interior layout (walls, doors, et cetera). These layers could be expected to change during renovation. Renovation waste flows can, therefore, have a very different consistency compared to regular construction waste, as they result from various actions, such as kitchen renovation, the addition of dormers and extensions, enhancement of insulation for improved energy efficiency, and more.

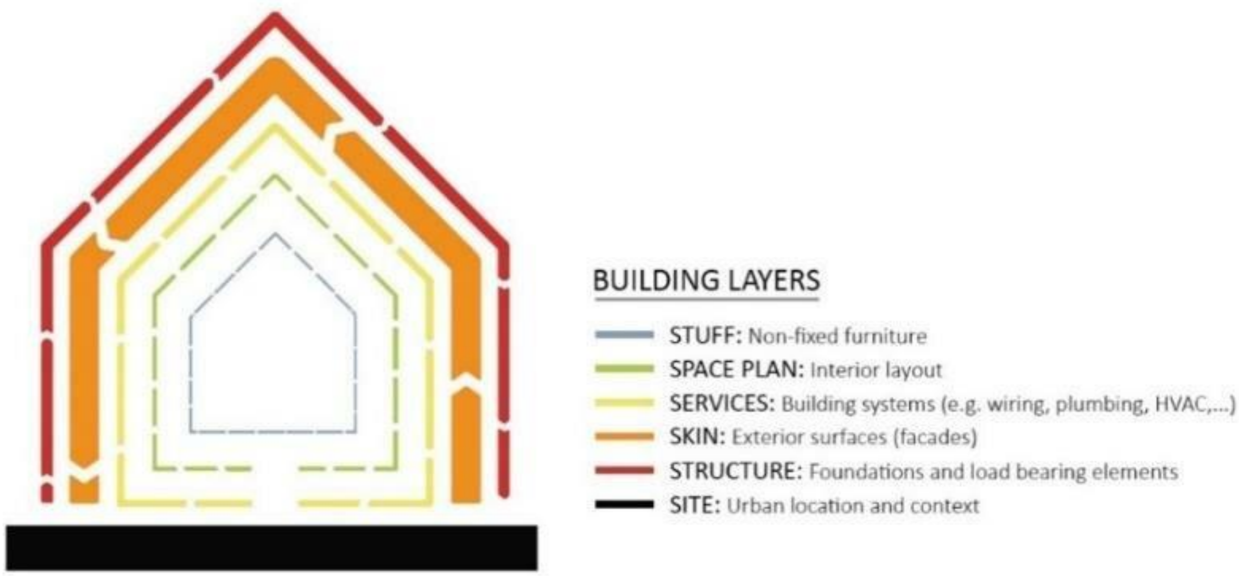


*Figure 1.1: the shearing layers of change by Stewart Brand (Imam & Sinclair, 2023).*

## 1.2 Background

It is important to understand what is meant by renovation as this is the main focus of this research. Leskovar & Premrov (2019) formulated it as: *"the process of improving or modernizing an old, damaged or defective building. Renovation, therefore, leads to improvement which displays better physical conditions, enhanced functional performance or even a changed use of a building".* It should be considered that the changed use is often referred to as transformation in the working environment. Using the original definition on renovation by Leskovar & Premrov (2019), transformation can be defined as: an improvement which displays better physical conditions, enhanced functional performance and a changed use of the building. A literature review by Vilches et al. (2017) showed that next to the term renovation, retrofitting, refurbishment, repair, and restoration are used in a similar way. Where refurbishment can be considered closely related to renovation, restoration is specifically for historical buildings, often monumental, with the means to return the building to a preferred earlier condition (making it often highly constrained). Henceforth, renovation is often used to cover renovation and transformation practices, unless there is a specific difference for which renovation and transformation are both named.

Following these definitions, I would expect the amount of material per floor area from transformations to be higher than that of renovations, due to the intense nature of transformations (Itard & Klunder, 2007). I would also expect a larger variety of different materials for a transformation project, as it usually includes the whole of the building, whereas for renovations, it depends on the type; a kitchen and bathroom renovation could generate, e.g., tiles, and sinks but a focus on energy efficiency improvement could generate, e.g., insulation material, which is also a lighter material.

Renovation has been studied following the Life Cycle Assessment (LCA) approach by several researchers. Hasik et al. (2019) compared renovation to new construction in Philadelphia on an industrial building from 1948 during its product, construction and use phase, not considering the construction installation, use itself, energy, and water use. It was found that a reduction of environmental impacts of 53-75% can be achieved by maintenance and replacement during renovation compared to new construction. Huuhka et al. (2023) used LCA in combination with a Consequential Replacement Framework: “evaluate the immediate environmental impacts of decision-makers’ choices between retaining or replacing buildings”. They focused on $CO_2$ emissions and found that renovation was more climate- friendly than demolition and new construction in the cases studied in Finland. Similar results were also found by Bragadin et al. (2023), Meijer & Kara (2012), and Palacios-Munoz et al. (2019). Vilches et al. (2017) conducted a review of studies focusing on energy-related renovations, revealing a predominant emphasis comparing the environmental impact before and after renovation. However, studies that examined the effects of renovation on the building’s energy consumption found that, in general, increased insulation does not always correlate with a reduced environmental impact, as the increased material use negatively affects the environmental impact of the renovation as well (Lasvaux et al., 2015; Moschetti & Brattebø, 2017; Ramírez-Villegas et al., 2019). This finding shows that, even though renovation is preferred over new construction, there is a fine line to achieve the lowest environmental impact.

To consistently reuse materials, it helps to know in advance what will become available during renovation and demolition. Research has been done on mapping the stock of buildings in Vienna by Kleemann et al. (2016), for Singapore by Arora et al. (2019), and for Leiden, the Netherlands by Yang et al. (2023). They quantified the stock of the main materials of a city using various methods, thereby showing what can become available during the demolition of the building.

With renovation happening more often than demolition (Metabolic, 2020; Wiedenhofer et al., 2015), it is crucial to understand which materials become available during these processes to facilitate their reuse. However, the study of renovation materials has been challenging due to the varied sources of information and different regulations. Mohammadiziazi & Bilec (2023) investigated renovation flows in the US, focusing on the quantification and spatial distribution through photogrammetry and image processing techniques. Similarly, Sun et al. (2020) researched decoration and renovation flows within Shenzhen City. As mentioned by both, variations in building types and structures can be substantial, which limits the applicability of the findings to the context of the Netherlands.

One of the approaches to determine the stock of an urban region is to use Material Intensity (MI). It is described as “the material composition of various components in the built environment and is influenced by local external factors such as climate, geological activity, historical and economic development, resource availability, and architectural trends” (Gontia et al., 2018). This MI is often expressed in mass per area or mass per volume and can be used to calculate the entire stock by multiplying it by the floor area or volume of the building stock. Different methods to determine the MI will be discussed in the literature study (chapter 2). In this research, the material intensities specific for renovation and transformation will be addressed a rMI, tMI, or r,tMI.

## 1.3 Research Objectives

From a circular economy perspective, the ultimate goal is to reuse materials for similar purposes. However, quantifying and determining the content of the flows from renovation presents a considerable challenge. Therefore, this research's objective is to calculate the amount of renovation waste of different building types per floor area. This can help predict the size and the type of waste flows of similar building types in the future and estimate the potential of reuse/recycling from renovation. To achieve this objective, the following research question will be answered: “*How much waste and what type of waste is actually generated in renovation projects of buildings”.* This main question is divided into 4 sub-questions:

1. How can renovation waste flows be quantified?
2. What materials can be found in renovation waste?
3. What are the quantities of renovation waste for different building types?
4. What are the material intensities (MIs) of renovation waste per building type?

The first sub-question is addressed in Chapter 2. Chapter 3 describes the methods used in this thesis and addresses sub-question 2. Chapter 4 presents the research results related to questions 3 and 4, while Chapter 5 discusses these findings, including limitations and recommendations. Lastly, the conclusion can be found in Chapter 6.

Figure 1.2 provides an overview of how this research fits within the broader context of building renovation, highlighting the system boundary of this research. The figure captures the processes, stocks, and flows of key materials, including construction and demolition waste, wood, aggregates, gypsum, paper/cardboard, roof waste, and synthetic materials, all within the context of the Dutch building sector. The study focuses on the period from January 2021 to May 2024, and although it is geographically located in the Netherlands, only a small selection of the buildings is studied, covering dwellings, educational institutions, healthcare facilities, offices, and ‘other’ types of constructions. A distinction has been made between new construction and construction for renovation as well as End-of-Life demolition and demolition for renovation, as these focus on different aspects of the building. Waste from the demolition types is collected in skips and brought to the waste treatment company. From there, the materials are either sent to a reuse/recycling facility for material recovery and reintegration into production processes or disposed of through landfill or energy recovery. Although both demolition and renovation waste are processed by the same waste treatment companies, the quantification of demolition waste falls outside the scope of this research.

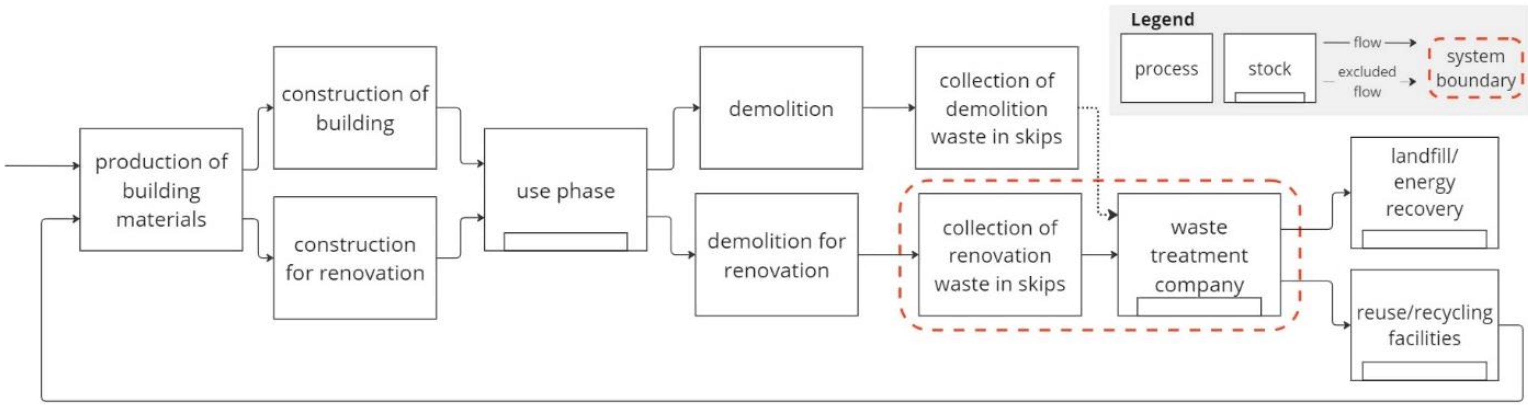


*Figure 1.2: Overview of material stocks and flows around renovation of buildings in the Netherlands and the system boundary of this study. Materials included are aggregates, gypsum, paper/cardboard, synthetic material, undifferentiated, and wood. The temporal scope is between January 2021 and May 2024. The geographical scope is limited to the Netherlands, however only a small selection of the total number of buildings in the Netherlands is covered. Construction type boundary: dwellings, educational buildings, health buildings, offices, and 'other'.*

# 2. Literature study

The literature study was conducted using the following search engines: Google Scholar, Web of Science, TU Delft Library, Leiden University Library. Search terms used include building renovation, building renovation residential, urban mining, material intensity building, and house renovation.

## 2.1 Material Intensity Calculation

Material Intensities (MIs) have been studied by numerous people as they are crucial for calculating material stocks in buildings. Tanikawa et al. (2015) describes 4 types: “top-down,” in which stocks are estimated using materials inflows and outflows; “bottom-up,” in which an inventory of buildings is multiplied by their average material content; “demand-driven,” in which stocks are estimated through proxies such as population and income; and “remote sensing,” in which satellite images are analyzed and used to estimate material stocks.” Regardless of the method, some researchers focus on determining the MI of buildings that are to be demolished (Kleemann et al., 2016; Sprecher et al., 2022). Others try to determine MIs in order to estimate existing building stock (Lederer et al., 2021). They might even calculate the MI for different purposes, e.g., analyzing the correlation between building size and material intensity (Miatto et al., 2023). Therefore, the articles discussed in this section focus on the derivation of the MI, and not necessarily on the estimation of the building stock. Different types of data sources are used, varying from construction manuals, machine learning, working drawings of existing buildings, or randomized samples of building (Lederer et al., 2021), to skip content (Sprecher et al., 2022), and photogrammetry and image processing techniques (Mohammadiziazi & Bilec, 2023).

Ortlepp's 2016 study introduces a method to quantify material stocks in Germany's non-domestic buildings by calculating MI for various building types, estimating total floor space, and assessing material stock. The research highlights a gap in current studies, which focus on energy consumption rather than resource efficiency, particularly for non-domestic buildings that represent 55% of Germany's total floor space. These buildings are diverse in function, construction, and materials, complicating material composition analysis. The study estimates floor area more accurately by updating gross volume data and converts monetary values into physical material stocks using national accounting data. Findings indicate that non-domestic buildings contain higher metal content due to larger spaces and spans, and they account for 42-45% of total material stock. The study underscores the need for more detailed material categorization to enhance recycling efforts and calls for increased focus on non-domestic buildings concerning resource efficiency, demolition, and material recovery.

The study by Gontia et al. (2018) details the construction of an MI database, focusing on the variables influencing MIs, the results, its limitations, and the importance of developing standardized MI databases for international comparison. The research centers on creating an MI database for residential buildings in Sweden, using descriptive texts, cross-sections, and architectural plans of 12 typical single-family and 34 multi-family buildings constructed between 1880 and 2010. The study categorizes data by house type (single-family or multi-family), structure type (wood, wood-brick, brick, concrete), and construction period, focusing on basic construction elements such as foundations, walls, ceilings, floors, windows, and roofs. Volumes of these elements are calculated from architectural plans, and masses are determined by multiplying these volumes with material densities from a German online database. MI is then derived as the mass per gross floor area (GFA) and aggregated by material category and building element. The study finds that MI values for single-family homes decrease over time, whereas the use of insulation materials increased starting from the 1950s. For multi-family buildings, MI depends on the structure type, with wood having the lowest MI and brick the highest. The study notes that 80% of the MI comes from minerals and finds higher wood and steel content compared to other studies. It also emphasizes the need for standardized MI databases, to enable effective international comparisons. The study does not cover renovation activities, which could influence MI, and notes that interior finishing materials and foundation pillars are not modeled, while assumptions include the use of triple-glazed windows.

The article by Ostermeyer et al. (2018) emphasizes the need for cities and governments to develop economically feasible pathways for refurbishing existing building stocks, particularly by integrating wood-based materials into refurbishment scenarios. It discusses the development of a building stock model (BSM) that includes component-specific data, which allows for assessing the synergies and conflicts between energy supply and demand on a large scale. Traditionally, materials have not been considered in energy efficiency modeling, but this article focuses on how wood can be used as a sustainable building material in refurbishment. The study improves on previous data by providing component-based information on refurbishment options, allowing for better assessment of embodied impacts. Buildings are clustered by construction year, type, and dominant technologies, with a focus on single, dual-family, multi-family, and office buildings, which constitute 72% of Switzerland's heated floor area. The database details material inputs and waste outputs for different refurbishment options, with a specific focus on wood, across various building components like walls, roofs, and floors. The study also highlights the impact of refurbishment on heat transmission coefficients, using a functional unit of 1 m² of building component floor area. While the life cycle assessment (LCA) considers only the new materials, it shows that wood-based refurbishment scenarios generate more waste and have a higher relative material impact, especially due to insulation materials. The article suggests that the next step would be to integrate this database with a national building stock model to evaluate the broader material usage and environmental impacts of refurbishment, including economic and labor costs.

Lederer et al. (2021) conducted a case study in Vienna to determine the MI of buildings using a random sampling of 256 objects, representing 0.11% of the total number and 0.22% of the total gross volume of buildings in the city. This method is useful when expert knowledge on conventional construction methods is limited, as it avoids the bias that would occur if only buildings slated for demolition were considered. The study, while highly detailed due to on-site investigations, may be less comparable to other studies as the sample was drawn from a GIS-based digital building model (DBM), provided by Vienna's municipal surveying department. The study utilized various data sources, including construction plans, databases, aerial photos, and Google Street View, to gather information, particularly regarding window installations before or after 1946. The MI was influenced by factors such as building age, use, volume, and whether the building had undergone renovations. The materials analyzed included concrete, brickwork, iron and steel, sand, gravel, stone, wood, mineral wool, polystyrene, glass, and gypsum boards. Material quantities were calculated according to Austrian standards for construction materials accounting, and MI was expressed in t/m³ using the formula MI = V*p/RV, where V is material volume, p is density, and RV is the reference value. Additionally, different story heights were applied, based on the building use category.

The study by Miatto et al. (2023) aimed to examine the correlation between the variations in geometrical and structural components of residential buildings and their MI, using an Italian case study. It involves determining average building sizes by typology, including single-family (concrete, wood), semi-detached (concrete, wood), medium, and large apartment buildings. Construction data from the Italian National Institute of Statistics and national design standards guide the composition of main building elements. To reflect real-world variability, 1000 buildings are simulated for each typology. The housing unit, including common spaces and parking lots, is the functional unit for comparison. Findings indicate that more housing units per building results in lower floor areas, volumes, and variance. Wooden structures take more roof volume but reduce "other materials" usage by 40% when compared to concrete. Medium-sized apartments have the highest concrete MI. On average, Italian residential buildings consume 1.5 ± 0.5 t/m². Single-family homes have the largest areas and highest material consumption, with concrete making up over 50% of their total mass. They recommend including a Life Cycle Assessment (LCA) of concrete and wood buildings to assess the impact of metals, noting that concrete use is driven by regulations, while other materials are influenced by customer preferences.

Overall, MIs are a valuable tool for estimating the material stock of buildings. Factors such as building age, volume, and whether it has undergone renovations significantly influence a building's MI. Most research has largely concentrated on domestic building types, and there is a growing call for national or even international standardization of MI calculation methods. Even though there is a large variation for calculating the material stock of cities or regions, which aids in estimating the materials available from building demolitions, less information is available on renovation waste.

## 2.2 Studies Focusing on Renovation

A systematic analysis by Sun et al. (2020) of decoration and renovation waste flows in Shenzhen City provides valuable insights into the complexities of waste management in urban environments. The Waste Generation per Area (WGA) method was employed which uses two key parameters: the building area and the waste generated per unit area (t/m²). They focused on two building types civil (including residential and public) and civic (such as tourism and education buildings). Notably, older residential buildings are assumed to generate 1.4 to 3 times more waste than newer ones. The analysis revealed that 72% of renovation waste in Shenzhen is composed of concrete and brick. Also, 83% of renovation waste is being directed to landfills. The trend of increasing waste generation is evident, with the total reaching 1.2 million tons in 2015. Although hazardous materials only constitute 2% of the total waste, their high environmental impact underscores the need for careful handling and disposal. The study highlights the growing necessity for additional sorting facilities to manage the diverse waste streams effectively.

The study by Mohammadiziazi & Bilec (2023) examined the material composition and material intensities of the commercial building stock in Pittsburgh, USA, with a focus on the following key building components: windows, walls, roofs, and floors. To estimate the surface areas of these components, the research utilized the footprint area, building height, floor count, and window-to-wall ratios. GIS data, specifically addresses and tax property IDs, were used to identify the building stock. Due to the absence of building height data, LiDAR analysis was conducted to determine building heights, while photogrammetry and image processing techniques were applied to assess exterior wall materials, floor counts, and window-to-wall ratios. The study categorized buildings into 20 typologies based on their material composition and construction type. The thickness and density of the materials in these typologies were then used to calculate the MI. Lastly, they calculated the total and annual material renovation flows expected between 2020 and 2030 by multiplying the floor area with the MIs, then summing the results while factoring in the service life of materials and the construction years of the buildings. They identified 12 different materials, some of which, such as carpet or felt and tar are typically overlooked in demolition but were relevant in renovation contexts. Among the building components analyzed, exterior walls emerged as the most diverse in terms of material types, with nine out of the twelve materials identified being present in this component. Brick was highlighted as having the highest cumulative mass in the renovation flows over the studied period, indicating its prominence in future material recovery efforts. The temporal analysis further revealed the timing of material availability, noting that materials like carpet, with a shorter service life, would become available sooner in the renovation cycle and brick or minerals later. They emphasize the importance of understanding material flows in renovation projects to enhance the potential for material reuse and contribute to more sustainable construction practices.

The study by Oorschot & Voet (2023) examines material demand for both renovation and new construction projects. It specifically focuses on the associated greenhouse gas (GHG) emissions from the production of various construction materials. The analysis distinguishes between the environmental impacts of using primary versus secondary materials, highlighting how the use of secondary materials can reduce these impacts. The materials under consideration come from demolition processes. The study evaluates three scenarios—a) biobased, b) circular, and c) conventional—to understand the different impacts. Additionally, the research incorporates end-of-life recycling rates of materials, considering not only best practices, but also actual values. They found that substantial emission reductions can be achieved by increasing recycling rates and the use of alternative materials, like bio-based and circular. Implementing circular construction strategies, in particular, directly reduce emissions by enabling lighter structures and facilitates recycling and reuse of materials at the end of a building's life cycle. While the use of bio-based materials lowers greenhouse gas emissions, side effects can be expected due to the large area required for wood production. The study also states that closing material loops will remain limited until at least 2050, as the building stock continues to grow, and end-of-life recycling rates are still low. Not only new construction but also the sustainability improvement of the existing building stock will lead to a substantial demand for materials, particularly non-mineral materials such as glass, insulation, metals, and plastics. Renewing the building stock will generally result in a higher demand for materials than improving the energy performance of existing buildings. However, extending the lifespan of buildings will also lead to increased material demand for building maintenance.

## 2.3 Application of Skip Data for MI Calculation

Sprecher et al. (2022) present an extensive database detailing the material intensity of Dutch building stock, drawn from 61 large-scale demolition projects and comprising 781 data points obtained from a demolition company. The data points represent over 306,000 square meters of built floor space and accurately reflect the characteristics of buildings commonly demolished in the Netherlands. The data were gathered in collaboration with a demolition company that emphasizes material and component reuse and recycling. They distinguished between two types of material flows in circular demolition practices: those related to the building's structure and those associated with building components, as these materials are handled differently during the demolition process. The BAG3D dataset was used to cover information on building types, sizes, construction years, and the number of dwellings per building.

They found that the non-office utility buildings have a remarkably high variability explained by a large variety in functionality, meaning a less uniform building design. They compared the MIs found with existing literature raising their confidence in the accuracy of the detailed classification into separate materials. Their research significantly expanded the number of data points available and provided more detailed insights into the types of materials found in demolition waste streams.

## 2.4 Key Findings

The literature review reveals that renovation waste has not been extensively studied, with existing research predominantly focusing on quantifying materials of complete demolitions of a building stock or determining the materials required to perform renovations. These studies often employ bottom-up approaches using models or case studies that are highly specific and may not be representative of other regions. The research on renovation and decoration waste flows is a good start in attempting to quantify this type of waste, however it is difficult to apply the results to other regions, as construction materials might be completely different, resulting in a different waste stream. Expanding the research to a different geographical area could address this issue, but the question remains how much renovation waste is generated for each building type. A top-down approach using skip data could fill this gap, though it has only been applied to demolition projects so far.

Given the significant variation in renovation types, a bottom-up approach through, e.g., modelling may prove challenging for this research. Hence, investigating accessible skips on-site could provide information on the actual waste generated during renovation. A back-up plan would be to use a top-down approach by acquiring data on the mass of the skips used during renovation. This top-down approach could provide a practical solution for accurately quantifying renovation waste.

# 3. Method

Figure 3.1 shows an overview of the research steps of this thesis.


*Figure 3.1: overview of research steps. The literature study can be found in chapter 2; the remaining steps are presented in chapter 3.*

## 3.1 Skip Investigation

Multiplying the content of the skip with the number of times the skip gets emptied per project provides the total amount of material from a renovation project. I reached out to the municipality and undertook fieldwork to acquire the locations of the skips.

### 3.1.1 Municipality

I reached out to Yvonne van Delft through email who is the council member for Energy, Work and Income, and Culture requesting the locations where permits had been issued for skip placement on paid parking lots during April, May, and June in the municipality of Leiden. From there I was connected to Martin Braam who is the team coordinator for licenses in public places. After a considerable wait, I received information on nine locations by email. The provided data included only street names, which made it difficult to locate the skips, especially on long streets. Additionally, some permits were only valid until mid-April, and by the time I received the data, it was already mid-April, leaving little opportunity to investigate those skips.

### 3.1.2 Fieldwork

I used the information from the municipality to find skips, but I anticipated that exploring the city more thoroughly would uncover additional skips. These might be located on private property or placed without a permit. I intentionally avoided the historic city center, as the limited space makes it difficult to place skips, and I expected the proportion of residential buildings there to be smaller due to, for example, residential buildings being situated above shops. It's also possible that these buildings are more likely to be rental properties, where maintenance is managed by housing corporations and private renovations are less likely.

I focused my exploration on specific neighborhoods with a high density of residential houses, where skips are more commonly found. Ultimately, I conducted two sessions, focusing on new regions during each session. Each session lasted an hour, and I located 32 skips in total. I did not include flats in this search, as I expected that private renovations are less likely and, therefore, skips would typically not be found around these types of buildings.

When a skip was found, I took a photo to document its contents. I used the app called 'Map Marker' that allows you to pin locations and add descriptions to record the skips (Map Marker, 2024). Each pin was numbered and corresponded to a numbered photo. For privacy and data security reasons, the specific location of the skip was not included in the photo overview. I documented the general content of the skip, its size, and the company name. A map with the locations can be found in figure A.1.1.

### 3.1.3 Skip Types

There are different types of skips available for rent, each designed for specific types of waste. Using the correct skip type increases the likelihood of proper recycling. The type of skip required depends largely on the nature of the project. However, one must be aware that the skip types available for private renters that perform renovations are not necessarily the same as for large companies and might not be used in the same way due to the space available and the amount of waste generated. Skip types for larger projects coordinated by a company can include, but are not limited to: Aggregates, Asbestos-containing material, Construction and Demolition Waste, Glass, Gypsum, Hazardous waste, Insulation material, Metal, Other, Paper/cardboard, Roof waste, Synthetic material.

Van Diemen (2024), a demolition and renovation company in Leiden, provides an overview of the skips that can be rented by private individuals on its website. These are also the types that you'd expect to see easily on the street. The skip sizes that can be rented are 3, 6, and 9 $m^3$. The types of skips that can be rented are:

- Wood waste (houtafval): for disposing of wood materials.
- Aggregates (puinafval): for gravel and similar materials
- Green waste (groen afval): for organic waste, such as garden trimmings.
- Soil and sod (grond en zoden): for soil and sod disposal
- Construction and Demolition Waste (Bouw en Sloop Afval): a general-purpose skip used when other specific skips are not applicable. This skip often contains the most diverse range of waste, making it the most expensive to treat. It's a convenient option, especially for smaller renovation projects, as it accommodates various materials like wood, metal, gravel, and synthetic materials. This versatility is particularly useful when space is limited, and placing multiple skips is not feasible. Section B.1.3 in Appendix B shows an overview of the average consistency found in construction and demolition waste collected by Prezero.

## 3.2 Interviews

Since the skip investigation failed to yield quantitative data, I conducted interviews with companies, academic experts, and contractors involved in renovations.

### 3.2.1 Company interview

During the in-person interview with the demolition and renovation company Van Diemen, I asked them for:

- The locations of their skips.
- How many skips they rented out in 2023.
- How often the skips get emptied.
- For what type of renovation a skip is rented.
- Who rents the skip (private-owner/contractor).

- Where the content of the skip is brought to.

I also spoke to the waste treatment company GP Groot through an online meeting asking about:

- If they keep track of the project types.
- How the recycling of materials is handled.
- What the quality of the materials is.

I also visited this company in Alkmaar where Jeffrey van der Burg, team leader functional application management, showed me around the waste treatment at GP Groot. I followed the natural flow of conversation, and I asked the following questions:

- How is the Undifferentiated waste treated?
- What happens with soiled wood?
- How is the mass determined?
- What do they do with the sorted materials?

### 3.2.2 Expert interview

I had a semi-structured in-person interview with Benjamin Sprecher. I followed the natural flow of conversation, and asked the following questions:

- If he had looked at renovation waste before.
- How he would approach this research
- What his experience was with holding interviews

I also had a semi-structured interview with Teun Verhagen, who works on the renovation topic at the company Van Wijnen. I asked the following questions:

- What is your own research about?
- How would you approach my research objectives?

### 3.2.3 Contractor interview

I selected contractors based in Leiden that conduct renovation work (Aannemer Nu, 2024). For the 80 contractors found, I wrote down the following features:

- The size of the company:
  - 1
  - 2-4
  - 5-9
  - 10-19
  - 20-49
  - 50-99
- The type of company:
  - Sole proprietorship (eenmanszaak)
  - General partnership (onder firma)
  - Private limited Company (BV: besloten vennootschap)
- The type of work by the company:
  - General residential and non-residential construction (algemene burgerlijke en utiliteitsbouw)

- Engineers and other technical design and consultancy services (ingenieurs en overig technisch ontwerp en advies)
- Demolition of buildings
- Construction carpentry (bouwtimmeren)
- Braiding reinforced steel (vlechten van betonstaal)

With this information, the smaller companies were reached out to first, as I expected that they would answer themselves instead of having a secretary for this. After, I reached out to the bigger companies as they might have more information on the waste quantity. I made a large selection, expecting a large number of contractors to be too busy, but also to obtain a different types of projects.

The questions for the contractors were:

- What type of renovations do you perform?
- What materials do you remove from the buildings?
- Do you know how much waste is generated?
- Are there elements that need to be replaced by a different material?
- Are there materials that do not return after renovation?
- What is the quality of the removed materials?
- Do you consider how you remove the materials to increase the chance of reusing?
- Is there a difference in the amount of material that is removed/put back?

Unfortunately, only one contractor was interested in an interview (see section 4.1.4.2). Therefore, I emailed eight renovation companies located over the Netherlands. I sent them a mock Excel sheet to show what data I required and what calculations I would do with the data. The material streams were based on Heeren & Fishman (2019). However, these could be adjusted to the information available at the company. I requested the location of each project to be able to find the construction year and the floor space in the BAG data set (Esri Nederland, 2024). I added a column in case a material stream was provided in a different unit and conversion was necessary. Again, only one company was willing to cooperate (RT Sloopwerken). However, at that time, I had acquired a substantial amount of data on renovation projects through Teun Verhagen. Therefore, I did not pursue this approach further to limit measurement uncertainty, but it is worth noting that it remains a viable option for data collection.

## 3.3 Data on Renovation & Transformation

I acquired data on the skip content of renovation and transformation projects through the connection with Teun Verhagen from the company Van Wijnen in the form of Excel sheets, called R&T and RT-BVO. R&T and RT stand for renovation and transformation; BVO stands for Bruto Vloer Oppervlak, meaning Gross Floor Area (GFA).

### 3.3.1 Project information

The R&T sheet provided data on the content of 8748 skips used during 358 renovation and transformation projects on buildings between 2021 and 2024 in the Netherlands. Table 3.1 provides an overview of the information found in the data.

*Table 3.1: Overview of information found in the R&T data sheet*

| Column names | Explanation |
|---|---|
| Project number | Each project has a number which was used to connect information on the mass with the floor areas |
| Project description | The project description contains different types of information. Sometimes the street name or building name is provided. Sometimes the number of houses renovated during that project in a specific city is mentioned. The type of renovation is also sometimes noted. Unfortunately, some project descriptions provided, e.g., only a city name. This did not provide enough information for me to find the total floor area of that project and construction year, needed to complete the r,tMI calculation. |
| Date | Each skip has a specific date mentioned. The dates of the dataset range from January 2021 – May 2024 |
| Waste treatment company | Seven waste treatment companies: BNext, Hartog, L'Ortye, NNRD, Prezero, Prezero West, Van Happen. |
| Eural code | The Eural code is a six-digit unified code for the classification of waste in the EU, mandatory during transportation of waste. Approximately 840 waste streams have been specified. Each country has guidelines to classify waste with the correct code. (European Commission, 2024) The Eural code is not of importance at the waste treatment facility as only the rough waste streams are separated (see below) |
| Waste stream | Asbestos-containing material, Construction and Demolition Waste (CDW), Roof waste, Hazardous waste, Gypsum, glass, Wood, Insulation material, Synthetic material, Metal, Other, Paper/cardboard, Aggregates*. (The names of the material waste streams are the same as the skip types except for CDW which will be addressed as Undifferentiated from here on.) |
| Mass (kg) | The mass of the material found in the skip |
| CDW (construction and demolition waste) mass (kg) | This column shows only the Undifferentiated values of each project. However, the values are the same as the Undifferentiated value in the mass column. Therefore, the column was not used to avoid double counting. |
| Volume | Not considered as the volume of skips is standardized. Therefore, this would not provide specific information per project. It also had fewer data points than Mass. Additionally, in the literature, the unit used for MI is mass per floor area. |

*Translated from: asbesthoudend materiaal, bouw-en sloopafval, dak-afval, gevaarlijk afval (KGA), gips, hout, isolatiemateriaal, kunststof, metaal, overig, papier/karton, puin.

### 3.3.2 Gross floor area

The Project numbers RT-BVO Excel sheet contains floor areas (BVO: Bruto Vloer Oppervlak (gross floor area (GFA))) of 156 projects. Unfortunately, again, only 71 were the same as the projects mentioned in the RT Excel sheet. This limited information was used, which meant I had to look up the floor area of the remaining projects by hand (see section 3.5.1).

## 3.4 Data treatment

Figure 3.2 shows the steps I took from when I acquired the data to get to the results I needed to answer the research questions. I cleaned the data by checking for irregularities. Of the 8748 skips in the list, some had a weight of zero or no value at all. This means the skip was not used during the project and is thus empty when brought back. These skips have been removed from the data as they did not contribute to the materials from renovation and will influence the statistical analysis of the mass. Three skips containing a negative value have been removed for now. This leaves a total of 8088 skips.

I categorized all the projects into their building type (section 3.4), separated the renovation and transformation projects (section 3.5), classified the buildings of the projects to a construction year category (section 3.6), and lastly, added the floor area for the buildings of each project (section 3.8). I then grouped each material per building type. I divided the mass of each material for each project with its corresponding floor area to obtain the MI (section 4.2).

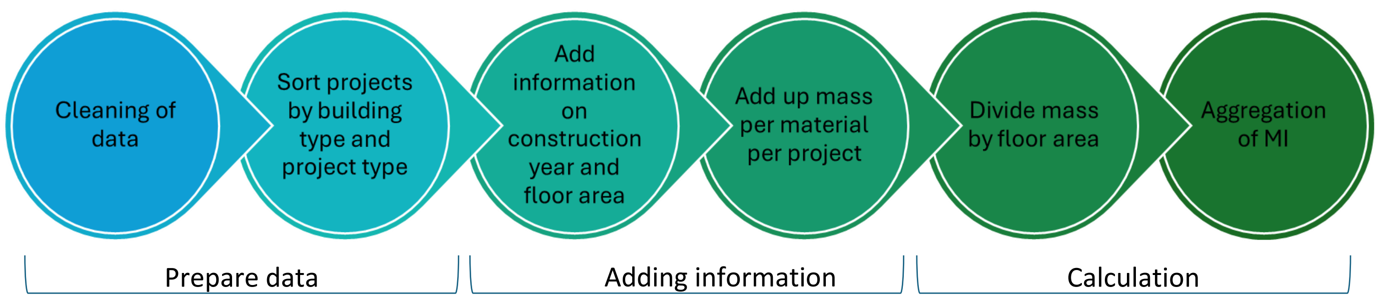


*Figure 3.2: Overview of data plan*

### 3.4.1 Building type selection

I used the building types by Tabula to organize the dwelling projects (Tabula, 2017). This website provides an overview of the most common houses in a country with information on, among others, energy use, the possible improvement of energy usage after renovation, and the energy distribution among the different parts of the building.

The following list shows the housing types found in the Netherlands by Tabula:

- Generic
- Detached
- Semi-detached
- Middle row
- Corner

- Common staircase and galleries
- Common staircase, no galleries
- Maisonnettes

Of the 358 projects, I was able to identify the building type of 303 projects using the project descriptions and the following websites (Acantus, 2024; Elkien, 2024; Google Maps, 2024; Huispedia, 2024; Kadaster, 2018; KadastraleKaart, 2024; Thus wonen, 2024; Van Wijnen, 2024; Vesteda, 2024; Wierden en Borgen, 2024; Wold&Waard, 2024; Woon Friesland, 2024).

Unfortunately, the fact that sometimes limited information on the project was provided, or that the project included multiple building types, e.g., semi-detached, detached, and row houses, made it difficult to assign the projects to each building type. Also, the data includes offices, hospital, and educational buildings. Therefore, I looked at the literature to help make a classification.

According to Ebrahimigharehbaghi et al. (2020), apartments make up 25% of the housing types in the Netherlands, row houses 42%, of which 12% are corner houses and 30% are middle houses, detached houses only make up 8.4% of the total housing types and semi-detached make up 11.3%. The report by Metabolic (2020) showed a large variety of building types as well. Van Oorschot et al. (2023) aggregated these to detached houses, row houses, apartments, industry, services, retail, office, other, placing semi-detached houses with detached houses, and aided housing under health. Sprecher et al. (2022) made the distinction between detached houses, row houses, apartments, high-rise, utility: offices, utility: commercial, and utility: other.

Table 3.2 shows the building types I decided to work with, also providing the number of projects per building type.

*Table 3.2: Number of projects per building type*

| Residential detached | Residential row | Residential apartment | Educational | Health | Office | Other | Total |
|---|---|---|---|---|---|---|---|
| 32 | 79 | 65 | 14 | 28 | 42 | 43 | 303 |

It is important to note that Educational and Health have been added compared to Sprecher et al. (2022) and van Oorschot et al. (2023), as it was possible to identify these. Health consists mostly of hospitals, which are a very specific type of building and are expected to be different in height and layout compared to the other building types. Industry (e.g., distribution centers) has not been added as a category as this was not found in the data. Commercial/Retail was only found in approximately six projects and was therefore added to 'other' (see also table 3.3).

To simplify the building types to one per project, I placed semi-detached houses (approximately 14 (partial) projects) with row houses, as I expected them to be more similar in construction and size, than the detached houses as they were found to be more varied, e.g., villas, former farms houses, and mansion-type buildings. I therefore also decided to place corner houses and middle houses together under row houses.

The different functions and building types in the 'other' category are provided in table 3.3. The results per building type can be found in section 4.2.1.

*Table 3.3: building types/functions found in the 'other' category.*

| | | |
|---|---|---|
| Airbase | Red cross | Temple |
| Dentist | Unknown | Daycare center |
| Courthouse | Sport hall | Bakery |
| Art library | Metal recycling company | Waiting area train station |
| Supermarket | Wholesaler | Service store train station |
| Church | Food bank | Laboratories |
| Shopping mall | Swimming pool | Former industrial building |

### 3.4.2 Renovation vs. Transformation

I separated renovation and transformation projects based on the project descriptions. Of the 303 projects, 21 are specified as transformation projects, and 282 as renovation project. Table 3.4 provides an overview of the original building types and functions and the new building types and functions, including the frequency of the transformation projects.

*Table 3.4: Types of transformation and the frequency*

| Former building type | Former function | Current building type | Current function | Frequency |
|---|---|---|---|---|
| Other | Vacant building | Other | Dental care | 1 |
| Office | - | Apartments | - | 6 |
| Other | Unknown | Apartments | - | 1 |
| Other | Art center | Apartments | - | 1 |
| Other | Store | Educational | University | 2 |
| Other | Church | Apartments | Apartments | 1 |
| Other | Red cross | Apartments | - | 1 |
| Educational | School | Apartments | - | 2 |
| Office | - | Educational | School | 1 |
| Other | Warehouse | Apartments | - | 1 |
| Educational | School | Office | - | 1 |
| Other | Klooster | Apartments | Aided living | 1 |
| Other | Store | Office | - | 1 |
| Other | Meat hall (monumental) | Office | - | 1 |
| # projects | | | | 21 |

### 3.4.3 Construction year categorization

I decided to follow the construction year categorization by Metabolic (2020), as they used the materialization of the different building elements as argument for their classification, which I expect are the parts that are most likely replaced during renovation.

The construction year categories from Metabolic are also similar to the breaks visible in the data (see figure B.1.1 in Appendix B). Furthermore, I expected renovation to be less common in recently constructed buildings, therefore the last category already starts in 2000.

- Before 1945
- 1945-1970
- 1970-2000
- 2000 and later
- Year unknown

I found the construction year of the buildings in the BAG viewer while looking up the floor areas of the building (section 3.5.1) (Kadaster, 2018).

### 3.4.4 Material selection

I decided to not consider any material with less than 15 projects and/or less than 1% mass. This is because there would not be enough data points to actually be able to show differences between building types and construction years. An overview of the mass percentages and number of projects per material, and for renovation and transformation separately can be found in Appendix B.1.2.

Therefore, I considered the following list of materials in this thesis:

- Undifferentiated
- Gypsum
- Wood
- Insulation materials
- Paper/cardboard
- Aggregates

## 3.5 rMI and tMI calculation

I calculated the rMI and tMI by dividing the mass of each waste material per project by the floor area of that project (see formula 1).

$$\mathrm{r,tMI}_{\mathrm{i,j,k,l}} = \frac{\mathrm{M}_{\mathrm{i,j,k,l}}}{\mathrm{FA}_{\mathrm{l}}} \qquad (1)$$

r,tMI is the material intensity for renovation (r) and transformation (t) ($kg/m^2$), M the mass (kg), i the construction material, j the building type, k the construction year category, l the project (by project number), and FA the floor area ($m^2$).

### 3.5.1 Floor area determination

To calculate the MI, I used the floor area provided in the data for 71 projects. I found the locations of another 191 projects during the building type research (section 3.4.1). I used the online BAG viewer to find the floor area as it contains the 'residential object' ('verblijfsobject') floor area, meaning the floor area of the smallest area with its own entrance and address (Kadaster, 2018). This provided the data needed for 241 renovation and 21 transformation projects to use for the MI calculation.

The floor area of the different building types was found in the following manner:

- Detached houses: the building itself was present in the BAG viewer, providing one value for the floor area.

- Row houses: the floor area was mostly very similar for the entire street due to the similar construction style. In some cases, I used the average floor area if there was a slight variation in floor areas between the houses in the street. I then multiplied the chosen floor area by the number of houses renovated during that project.
- Apartments: the same approach as for row houses.
- Educational buildings: the building itself was present in the BAG viewer, providing one value for the floor area.
- Health buildings: the building itself was present in the BAG viewer, providing one value for the floor area. It should be noted that these areas are very large, due to the usually large size of establishments such as hospitals.
- Offices: the building itself was present in the BAG viewer, providing one value for the floor area.
- 'Other': sometimes the building itself was present in the BAG viewer, providing one value for the floor area. Otherwise, I used the average floor area in that location.

To analyze the data, the MIs of the renovation and transformation projects were then grouped together by material type, building type and construction year, and plotted as boxplots (figures 4.2-4.6).

### 3.5.1 Recycling possibilities

The End-of-life (EOL) recycling rate (RR) is the share of the waste flow that is recycled. The RRs of the materials studied in this research can be found in table 3.5. They are partially based on the overview provided by Van Oorschot et al. (2023) of the practical and ideal EOL RR of demolition waste and the following assumptions: I assumed aggregates to have a similar EOL RR to concrete mixes found on the Bodemrichtlijn (2024) webpage as the concrete mixes are described to mainly contain aggregates and masonry waste; I used an average EOL RR of 0.855 paper/cardboard (PRN, 2024); lastly, I assumed the renovation, transformation, and demolition RRs to be the same, since the materials are brought to the same waste treatment facility. I calculated the total amount of recycled material from the projects investigated during this research by multiplying the total mass of each material with its EOL RR.

*Table 3.5: Overview of End-of-Life (EOL) Recycling Rates (RR) of the materials studied.*

| Material | EOL RR | Source |
|---|---|---|
| Aggregates | 0.45 | Bodemrichtlijn (2024) |
| Undifferentiated | 0.95 | Hu et al. (2013) |
| Gypsum | 0.7 | Jiménez-Rivero & García-Navarro (2017) |
| Paper/cardboard | 0.83-0.88 | PRN (2024) |
| Synthetic material | 0.25 | ASBP (2021), Verhagen et al. (2021) |
| Wood | 0.76 | Mehr et al. (2018), Verhagen et al. (2021) |

# 4 Results

## 4.1 Type of Materials

### 4.1.1 Skip Research

#### 4.1.1.1 Municipality

According to the municipality of Leiden, nine permits for placing skips on paid parking areas were granted in the period between April 1st and June 30th. As this process was time consuming, by the time I got an answer, four of the permits were already close to expiring, making it impossible to conduct a skip investigation based on this data.

#### 4.1.1.2 Skip research

The skips found through fieldwork belong to the following companies: Van Diemen, van Leeuwen, Meeuwenoord Recycling, Renewi, Spelt, Vd Hadelkamp, VLK, Omega. The size of the skips varied from 3 $m^3$, 6 $m^3$, 9-10 $m^3$ and depended on the company and the project that is done. Most common skip size I found is the medium sized skip (found 17 times), then the large skip (seven times), least found is the small skip (five times). A map of the skips can be found in Appendix A.1.

Some skips looked very organized, e.g., roof tiles and bags, neatly stacked (see figure 4.1). However, most skips looked very messy and unorganized (figure 4.2). More images can be found in appendix A.2 showing a large variety of materials and dimensions of those materials, as well as some highly unexpected items for renovation waste: banana peel, hiking sticks, children's bike, et cetera (see section 4.1.3).

*Figure 4.1: 10 $m^3$ skip found in Leiden containing mostly roof tiles and other roof-waste.*

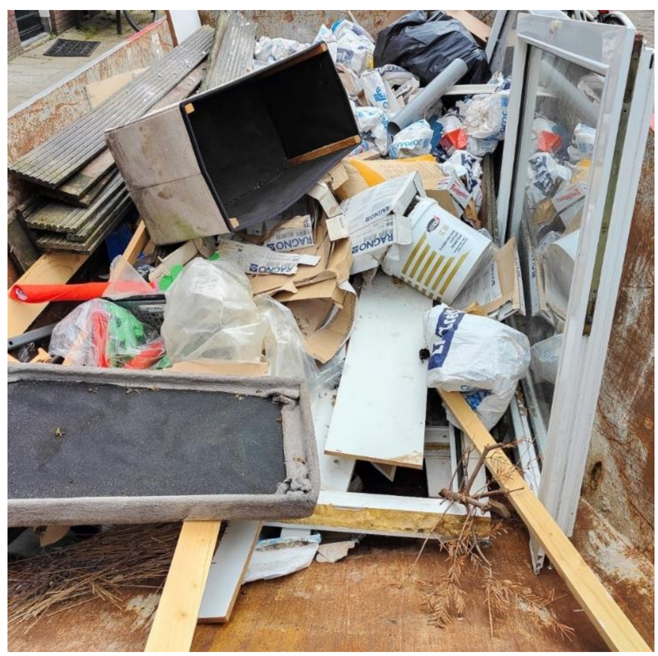

*Figure 4.2: 6 $m^3$ skip found in Leiden containing a large variety of materials.*

I was not able to quantify renovation waste from the skip research due to the following reasons:

- It proved difficult to examine the exact content of the materials. The skip is often filled to the maximum height allowed. This makes it difficult to see what lies underneath and materials are missed.
- It is difficult to categorize the materials. With the variety of materials that come out of a house, not just by renovation, it is difficult to aggregate this into meaningful material streams.
- It is impossible to quantify the mass by only looking into the skip, as materials are often too large to safely remove from the skip, and thus cannot be weighed.
- Skips are often emptied several times during the renovation project. To obtain information on the emptying frequency, collaboration with the skip renter or company is needed.
- Getting in touch with the skip renter is difficult as it is not always clear to whom the skip belongs when it is placed on the street.
- Not all projects have the same duration, therefore it is difficult to follow along (as just a master's student who also doesn't have all the time in the world for research). On the other hand, when the skip is rented for just one day, it is easy to miss when you are working alone.
- Not knowing where the skips are at the time of inspection makes it difficult for a single person to do the investigation. As the municipality only provided 9 locations for which a permit was issued, and one of the companies mentioned that they can rent out up to 700 skips on a day (with different rent times), it makes it difficult to select the ones that are accessible during the research without neglecting information.

#### 4.1.1.3 Materials found

The skips found in Leiden (most likely CDW type) provided a general overview of the materials and building elements that were found during renovation of row houses (see list below).

- Roof tiles
- Gravel/sand
- Roof insulation
- Street tiles
- Wooden beams
- Refrigerator
- Styrofoam
- Radiator
- Gypsum
- Toilet bowl
- Tiles
- Metal pipes
- Sink
- Packaging material
- Window frames
- Plants
- Furniture
- Trash bags (filled)
- Glass
- Chipboard

### 4.1.2 Interviews

#### 4.1.2.1 Company interview

Van Diemen knows where the skips are placed and could in theory provide information on the quantity of renovation waste per project. However, they rent out up to 700 skips per day for all different types of projects, making it extremely time consuming for them to sort out the renovation projects, for which they do not have the manpower.

The company does keep track of the number of times the skip gets emptied, however, this is only for financial interest of them, and with over 700 skips rented out per day, one person cannot go by to investigate all of these.

Skips are mostly rented when people need to work fast and they do not have time to bring the waste to the recycling center themselves. The people who rent skips are approximately 50% homeowners and 50% contractors. The waste from the skips is partially sorted by the demolition and renovation company themselves, after which it is brought to a larger waste treatment facility (such as GP Groot).

#### 4.1.2.2 Contractor interview

Of the 13 contractors in Leiden, I reached out to  by email, none replied. Calling them helped to get in touch, but only one was willing to actually have an interview with me, the others were not interested or did not have the time.

It seems that contractors did not know as much as I expected. Especially this sole proprietorship contractor was not aware of the exact amount of the materials that he removes from the houses he renovates. From the interview, it became clear that materials removed during renovation are often low in quality and therefore not reusable. This is a reason for the material to be put in a CDW skip.

Types of renovations performed include bathrooms, adding dormer windows, house extensions, fitting double glazing, energy efficiency improvement by insulating, et cetera. Materials/elements removed are, but not limited to, wood, porcelain, doors, radiators, toilets. Moreover, wooden window frames are replaced by synthetic window frames, façade cladding is replaced by synthetic material, and porcelain is being replaced by an acrylic alternative. Despite this, apparently older materials (30-50 years) make a reentry as being vintage. Lastly, rotten wood needs to be replaced entirely by new wood or an alternative material, whilst velux window frames are well-reusable.

If a contractor wants to use secondhand materials, these mostly come from large demolition projects. The materials then come in large amounts and in good condition, with this being especially the case for steel. Secondhand wood, however, is often not economically interesting for reuse, as it is only about 20% cheaper than virgin wood. This originates from the labor that needs to be put in to clean the wood. When the quality of the wood is then also questionable/lower than virgin wood, it is understandable that often virgin wood is preferred.

#### 4.1.2.3 Waste treatment company

According to GP Groot, the waste company is able to separate the waste quite well. They focus on separating the materials into more specific categories, for example, magnetic and non-magnetic metals, small and large aggregates, and A-, B-, C-type wood. It helps if the materials are sorted at the renovation site to reduce the number of steps. However, the construction and demolition waste skip type contains a large variety of materials. The materials from these skips are sorted by a large sorting system. It should be noted that this sorting system uses a lot of energy due to, among others, the number of sensors, conveyor belts, and extraction systems. After all the separation steps, synthetic materials are the type that are leftover the most frequent. The remains of the waste are used for energy recovery through combustion, whilst the separated materials are then mostly recycled, to be used as a resource for products.

## 4.2 Total material amount

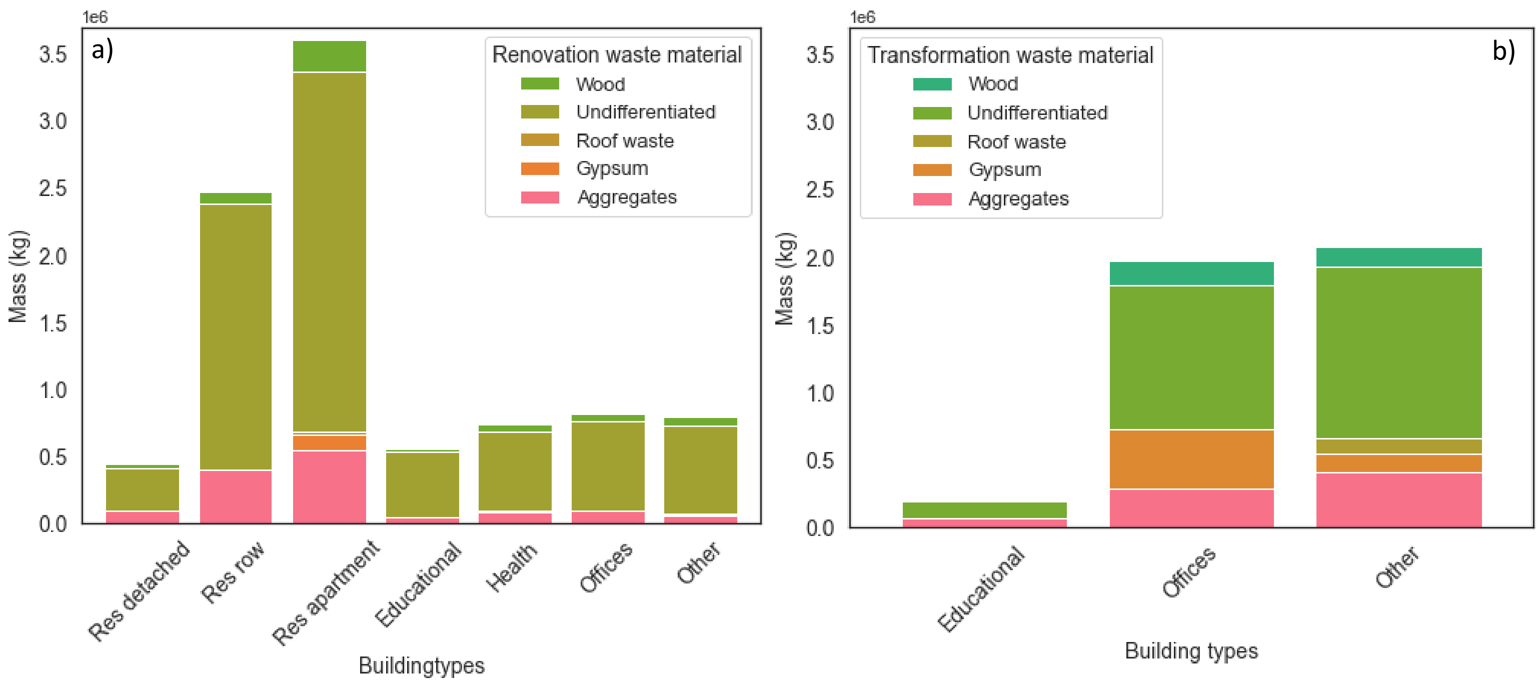


*Figure 4.3: Mass of larger renovation (a) and transformation (b) waste flows per building type of 282 and 21 projects in the Netherlands.*

Figure 4.3 shows the 5 largest waste flows for renovation (a) and transformation (b) per building type (section 3.4 of the methods). The renovation waste is based on 282 projects, whereas transformation is based on 21 projects. Note that 'Res' is used as abbreviation for residential.

Of the large waste streams, Undifferentiated is the largest contributor for each building type of both renovation and transformation. It is remarkable that renovated apartments generated 3.5 kilotons of material out of 63 projects, whereas row houses generated 2.5 kilotons out of 79 projects. Aggregates from renovation have a similar order of magnitude for all building types (detached: 8, educational: 4, health: 8, offices: 8, 'other': 8 projects, respectively) except for row houses (14 projects) and apartments (23 projects). Looking at figure 4.3b, it is remarkable that transformed offices and 'other' generated more waste from 7 and 11 projects compared to the renovated offices and 'other' with both 34 projects.

Figure 4.4 shows the 8 smaller waste flows for renovation (a) and transformation (b) per building type. Paper/cardboard is the highest for most building types, except for renovated detached houses and transformed 'other' where metal is the largest. Again, the most waste was generated by renovated apartments (135 tons from 63 projects), a similar amount was generated by transformed offices (140 tons from 7 projects). Row houses generated substantially less 'smaller' materials (35 tons from 79 projects) than apartments (135 tons of from 63 projects) when comparing to figure 4.3. Transformed educational buildings generated the least amount of waste (3 projects). An overview of the number of projects per material and building type for figures 4.3 and 4.4 can be found in appendix B.2.1 and B.2.2, respectively.

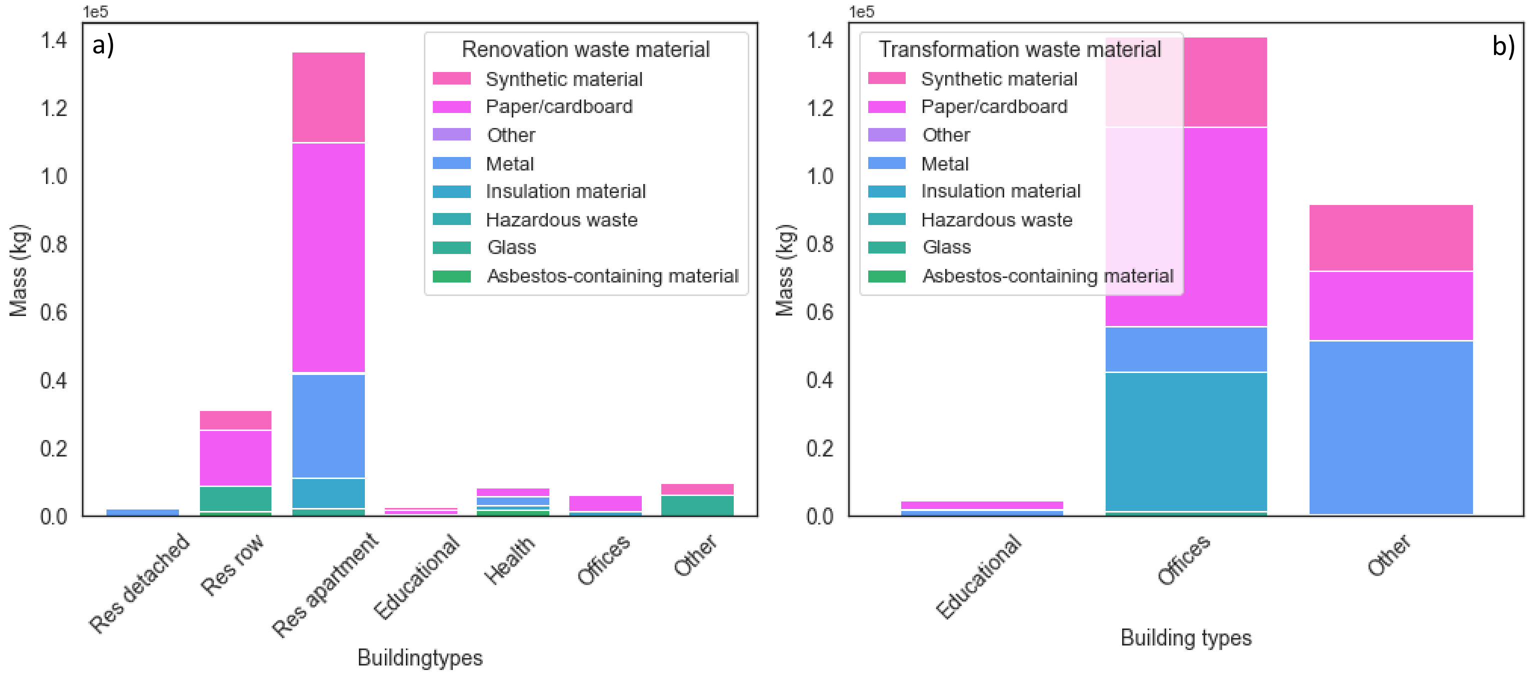


*Figure 4.4: Mass of smaller renovation (a) and transformation (b) waste flows per building type of 282 and 21 projects in the Netherlands.*

Figures 4.5 and 4.6 show the total amount of materials for renovation and transformation per construction year category.

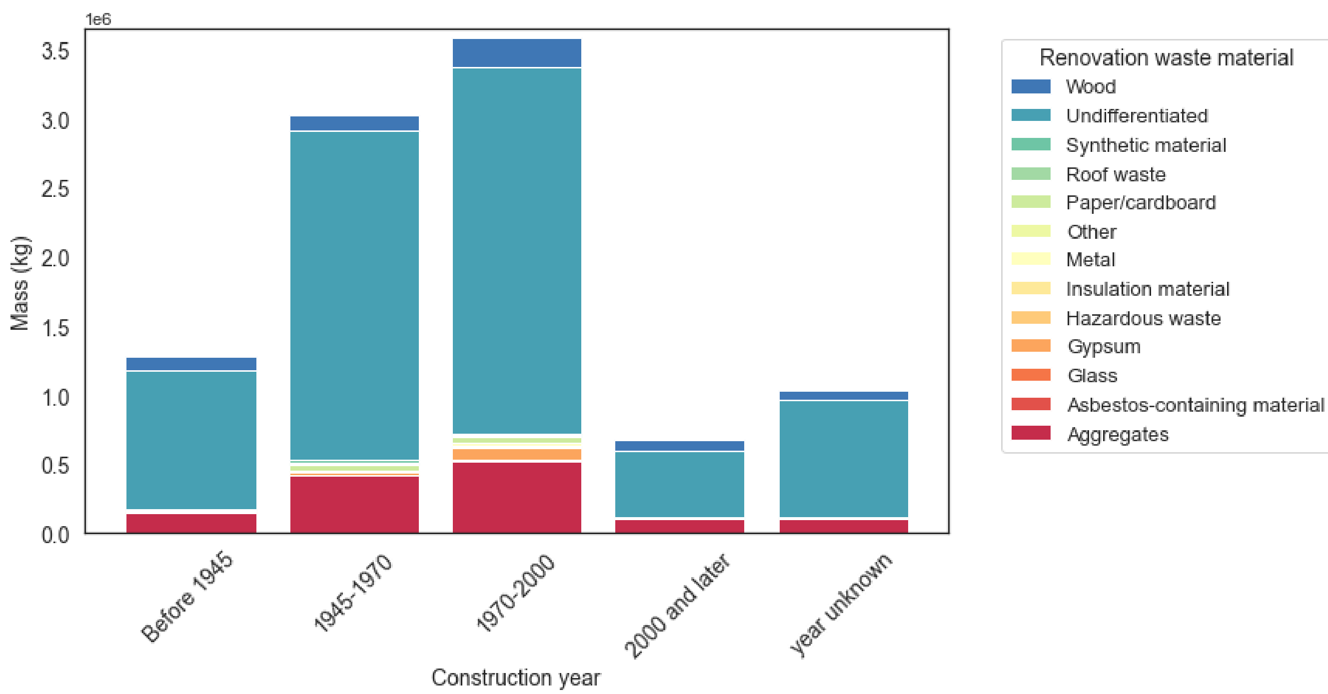


*Figure 4.5: Mass of renovation waste flows per construction year category of 282 projects in the Netherlands. Number of projects per category: Before 1945: 48; 1945-1970: 61; 1970-2000: 96; 2000 and later: 31; year unknown: 46.*

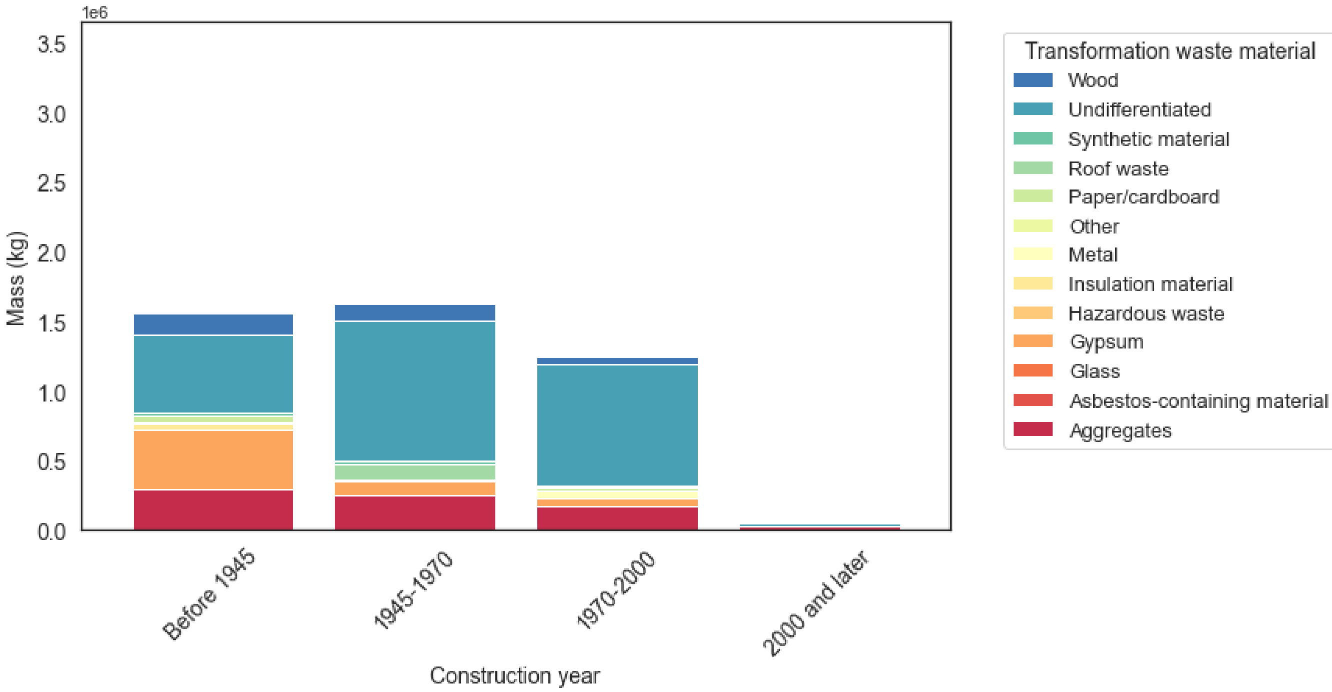


*Figure 4.6: Mass of transformation waste flows per construction year category of 21 projects in the Netherlands. Number of projects per category: Before 1945: 6; 1945-1970: 5; 1970-2000: 8; 2000 and later: 2.*

It is again notable that Undifferentiated has the highest share in each construction year category. The most renovated projects are on buildings from between 1970 and 2000 (96 projects), also generating the most mass (3.5 kilotons) followed by 1945-1970 with 61 projects (generating 3 kilotons). The most remarkable is the similarity in magnitude in the Before 1945 category, as renovation is made up of 48 projects, whereas transformation consists of 6. However, transformation of buildings from Before 1945 appear to generate a more diverse waste stream, with a larger share of gypsum and paper/cardboard and insulation material. Furthermore, renovation and transformation projects on buildings from 2000 and later are substantially less common with 31 and 2 projects respectively. Tables B.2.3 and B.2.4 in Appendix B show the number of projects for each material and construction year category.

## 4.3 Material Intensities

### 4.3.1 Material Intensities per building type

Figure 4.7 illustrates the amount of renovation waste material per square meter compared for each building type, excluding outliers. Note that each material has its own y-axis distribution with limits ranging between 1 kg/m$^2$ and 60 kg/m$^2$ and that not all materials are represented equally. In general, Undifferentiated and Aggregates have the highest upper limits from the maximums in offices and 'other', respectively. Synthetic material and Paper/cardboard have the lowest upper limits.

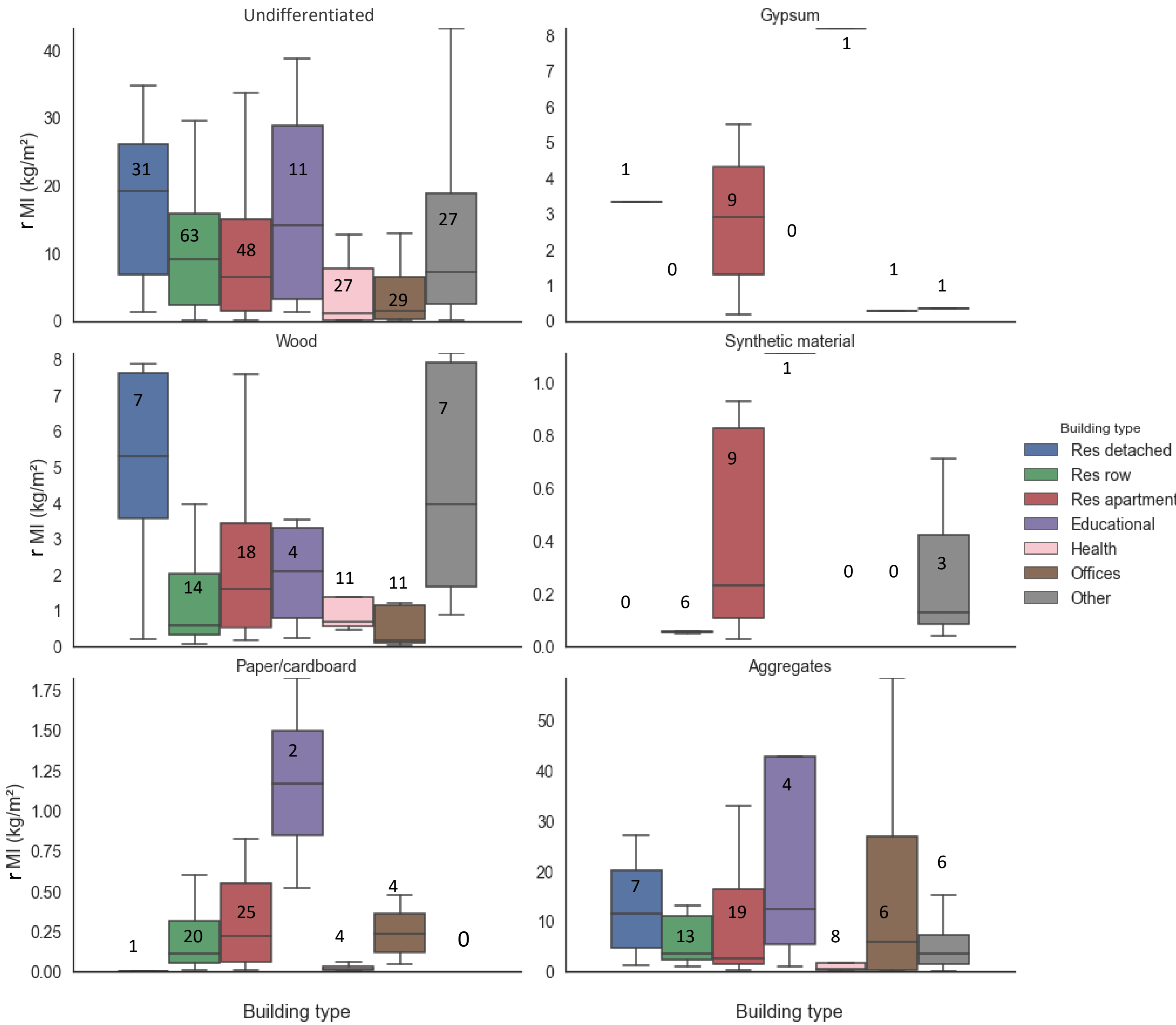


*Figure 4.7: Boxplots of rMI of renovation waste by material and building type. The numbers represent the number of projects that make up the boxplot including the outliers.*

Looking per building type, detached houses (32 projects) only clearly show Undifferentiated, Wood, and Aggregates with a rMI median of 20, 5.5, and 10 kg/m² respectively; Gypsum, Synthetic material and Paper/cardboard are barely generated (1, 0, and 1 projects respectively). Also, Undifferentiated and Wood have a much higher median for detached houses than for the other building types. In general, the maximum values of detached houses are closer to the third quartile than the minimum is to the first quartile.

Row houses (79 projects) generated all materials but gypsum. The median values are quite low compared to the other building types (especially detached houses), ranging ranges from 0.1 to 10 kg/m$^2$. Also, Undifferentiated and Wood have a maximum quite far from the median (30 kg/$^2$ and 4 kg/m$^2$) from 63 and 14 projects, respectively. Synthetic material shows a consistent rMI with a small variability for six projects.

Apartments (63 projects) are represented the best showing all materials with median values between 0.2 and 8 kg/m$^2$ also based on the most projects (except for Undifferentiated). Especially Gypsum and Synthetic material appear at 3 and 0.2 kg/m$^2$ as one of the only building types with Synthetic material having a very high third quartile, reaching 0.8 kg/m$^2$. Wood and Paper/cardboard are both higher for apartments than for row houses with wood showing an extremely high maximum value.

Educational buildings (11 projects) are a bit different compared to the dwellings, with a high median for Undifferentiated of 15 kg/m$^2$ and a maximum of almost 40 kg/m$^2$. However, Wood is around 2.5 kg/m$^2$ with a maximum of 3.5 kg/m$^2$. Gypsum and synthetic material are not found in the renovation projects of educational buildings. However, paper/cardboard has the highest median of all building types at 1.2 kg/m$^2$. Aggregates coming from educational buildings is around 10 kg/m$^2$ with a third quartile exceeding 40 kg/m$^2$ which is also its maximum.

Health (with 28 projects) is the building type with the lowest rMI values for each material type compared to the other building types, even though the number of projects is not necessarily less than for the others. It ranges from almost 0 to 3 kg/m$^2$, with the maximum for Undifferentiated around 12 kg/m$^2$ which is of similar magnitude as the median values of the other building types. The rMIs of health buildings are the most similar to offices in terms of number of projects and boxplot distribution except for the Aggregates waste stream where Offices has a maximum of 60 kg/m$^2$; the median of Aggregates is, however, better comparable to the other building types (approximately 5 kg/m$^2$.

The ‘other’ building type category (34 projects) is represented in four of the six materials with a noticeable rMI for Wood at 4 kg/m$^2$ with a maximum of 8 kg/m$^2$ and a very high maximum for Undifferentiated exceeding 40 kg/m$^2$. Also, it is the only building type not generating Paper/cardboard waste.

As previously mentioned, outliers are not depicted in the main figure. However, to provide an indication of the range these outliers cover: Undifferentiated includes approximately 15 rMI values around 100 kg/m$^2$, with one extreme case in the ‘other’ category reaching nearly 750 kg/m$^2$. Gypsum in apartments and wood in the ‘other’ category both have single outliers reaching up to 70 kg/m$^2$. Synthetic material in apartments reaches a peak outlier value of 4 kg/m$^2$, while paper/cardboard in apartments shows outliers at 1.5, 3.5, and 5.5 kg/m$^2$. Aggregates, which has the most outliers spread across various building types, generally exhibit fewer extreme values, with 8 outliers peaking at 120 kg/m$^2$ in apartments.

Figure 4.8, shows the amount of transformation waste material per square meter compared for each building type, not showing the outliers. The first notable observation is the presence of only educational, office, and 'other' as building type. Additionally, the y-axis limits for most materials are higher compared to those in Figure 4.7 (focused on renovation), with the exception of Aggregates.

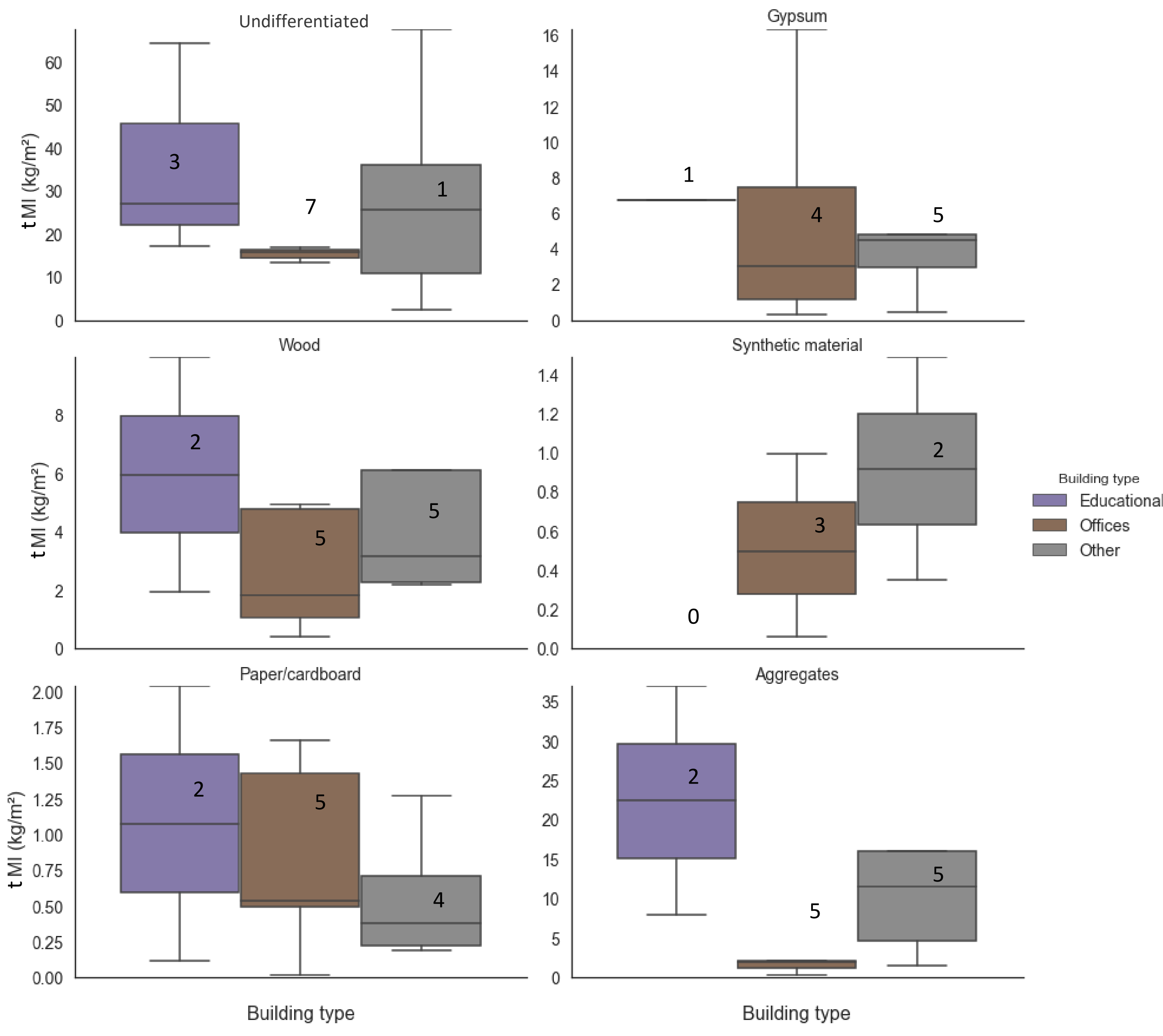

*Figure 4.8: Boxplots of tMI of transformation waste by material and building type. The numbers represent the number of projects that make up the boxplot including the outliers.*

Educational buildings (3 projects) show a similar distribution of the tMI for Undifferentiated, Wood, Paper/cardboard, and Aggregates but Gypsum, and Synthetic material is barely generated during these transformations. The medians range from around 1 $kg/m^2$ to 28 $kg/m^2$. however, the maximum value of Undifferentiated exceeds 60 $kg/m^2$.

Offices (6 projects) show different distributions of the boxplots than Educational buildings. The median values of all materials are also lower ranging from 0.5 $kg/m^2$ for Paper/cardboard and 15 $kg/m^2$ for Undifferentiated. Gypsum is similar to the other building types and even similar to renovated apartments at approximately 3 $kg/m^2$ but the maximum goes up to 16 $kg/m^2$. Aggregates is very low, around 2.5 $kg/m^2$ also compared to renovated offices which was around 5 $kg/m^2$.

The 'other' category (11 projects) ranges from just below 0.5 $kg/m^2$ to 25 $kg/m^2$. However, the highest maximum coming from Undifferentiated reaches up to 60 $kg/m^2$. Again, Gypsum and Synthetic material are represented equally in number of projects compared to the other materials.

In general, Educational appears to be higher than Offices, but the 'other' category does not follow this idea.

Outliers from transformation projects are relatively rare, with only six instances spread across four of the six materials. Undifferentiated has an extreme value of 1000 $kg/m^2$ for offices, and a more reasonable value of 200 $kg/m^2$ for 'other. Gypsum in the 'other' category has 12 $kg/m^2$, which is still below the maximum observed for offices (16 $kg/m^2$), whilst wood recorded an outlier of 25 $kg/m^2$ in the 'other' category. Lastly, aggregates show a maximum outlier for offices of around 10 $kg/m^2$ which is below the median of Educational (20 $kg/m^2$), but a much higher outlier of 120 $kg/m^2$ for 'other'.

### 4.3.2 Material intensities per construction year

Figure 4.9 presents the rMI of all renovation projects categorized by construction year. Although "Year Unknown" is included, the focus primarily lies on the construction years with identifiable data.

Looking at the number of projects per category, Undifferentiated, Wood, Paper/cardboard, and Aggregates are generated the most often, with Gypsum and Synthetic material staying behind. The last two are also the ones with the most variation of median between the different construction year categories. For most materials, the category between 1975 and 2000 has the highest median, except for Synthetic materials where 1945-1970 stands out.

Undifferentiated shows median values that are relatively close, ranging between 8 and 10 $kg/m^2$, with similar quartiles extending up to around 20 $kg/m^2$ and maximums between 35 and 40 $kg/m^2$.

Gypsum is observed in projects until the year 2000, with median values approximately at 2, 3, and 4 $kg/m^2$. The most variability occurs in the 1970-2000 category.

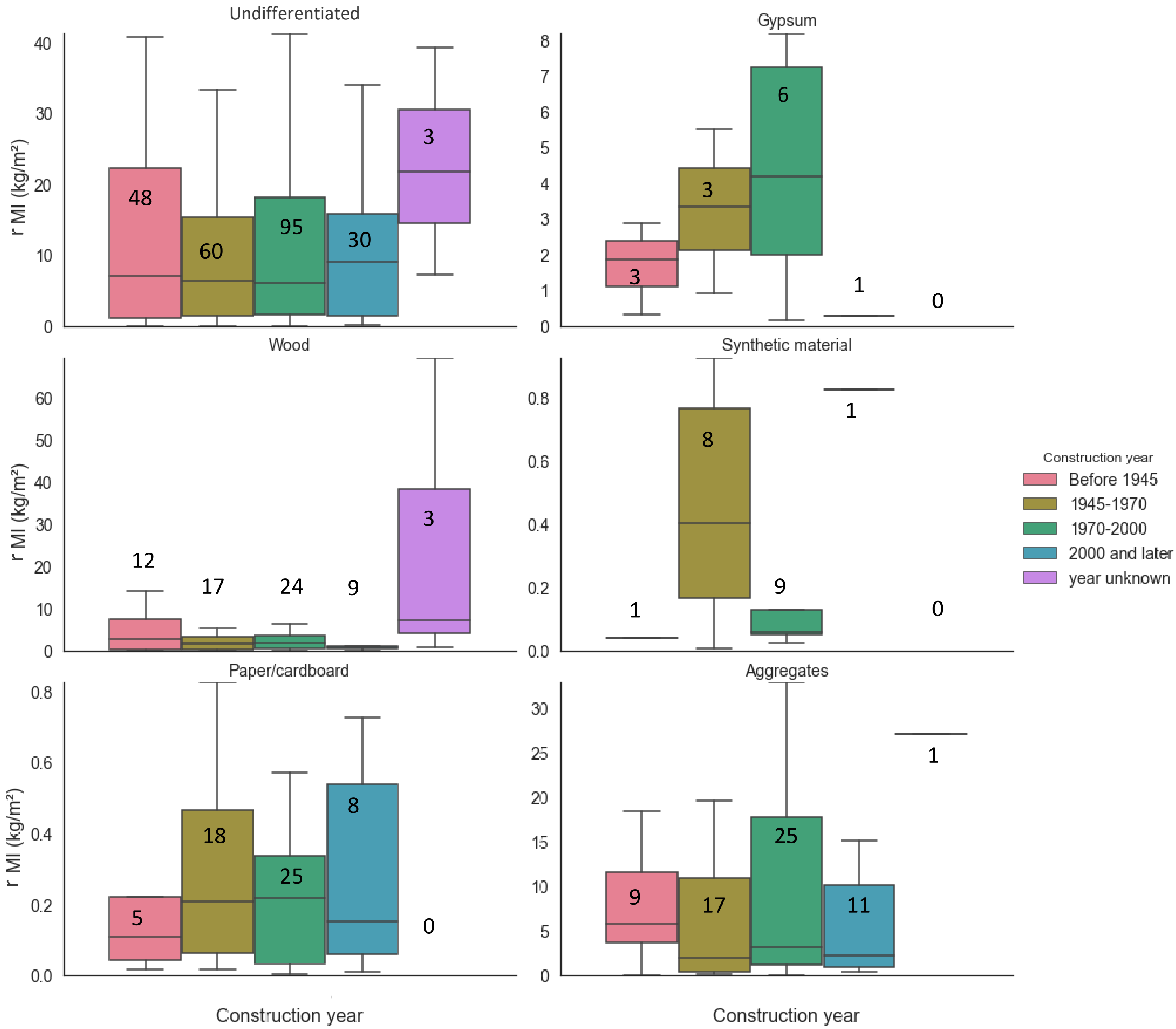


*Figure 4.9: Boxplots of rMI of renovation waste by material and construction year. The numbers represent the number of projects that make up the boxplot.*

Wood is challenging to analyze due to the "Year Unknown" category, which has an exceptionally high maximum compared to other periods and a median of around 8 kg/m². Despite this, the medians for the other construction years are relatively close, hovering around 2 kg/m².

Interesting to see that Synthetic material at 1945-1970 has quite a high maximum and median compared to Before 1945 but is again much lower for 1975-2000. 2000 and later shows a high median but consists of only a single project.

Paper/cardboard from Before 1945 shows a median of approximately 0.1 kg/m$^2$, whereas later periods have medians closer to 0.2 kg/m$^2$. The 1945-1970 period has the highest maximum at around 0.8 kg/m$^2$.

The median of Aggregates from before 1945 is circa 6 kg/m$^2$, whereas the later construction years show a median of around 3-4 kg/m$^2$. There are approximately 35 outliers observed in the data on renovation projects. For Undifferentiated, most outliers hover around 100 kg/m$^2$, though one extreme outlier reaches 700 kg/m$^2$ in the 1970-2000 construction year category. Gypsum has a single outlier of 70 kg/m$^2$ within that same period. Wood presents four outliers, with a maximum value of 22 kg/m$^2$, none of which exceed the third quartile of the "year unknown" category. Synthetic material has three outliers, one of which is around 3.8 kg/m$^2$ for 1945-1970, while  the other two from 1970-2000 align with the boxplot shape of 1945-1970. Paper/cardboard exhibit six outliers; the 1970-2000 category had three, with the highest at 5.2 kg/m$^2$, and the 1945-1970 category has one at 3.8 kg/m$^2$. Lastly, Aggregates shows outliers reaching up to 120 kg/m$^2$, with two outliers in this range, while the others fall between 40 and 80 kg/m$^2$.

Figure 4.10 presents the tMI of transformation waste across various construction years for all transformation projects. A key observation is that most materials exhibit a decreasing median tMI as construction years become more recent. Also, there are very few transformation projects from 2000 onward, while buildings constructed before 1945 and between 1945-1970 are well represented.

Additionally, all construction years were accounted for, with no data gaps. Lastly, it appears that the median value decreases for each more recent construciton year.

For Undifferentiated, the highest variability is observed in the 1970-2000 category, with a maximum value exceeding 60 kg/m$^2$ and a minimum of around 5 kg/m$^2$. This range might be attributed to the slightly higher number of projects in this period or possibly greater variation in building types, which is not visible in the figure. The median tMI is highest for buildings constructed before 1945, at 30 kg/m$^2$, followed by 20 kg/m$^2$ for 1945-1970, and 15 kg/m$^2$ for 1970-2000.

Gypsum shows a maximum tMI of 16 kg/m$^2$ for buildings constructed before 1945, with a median of approximately 7 kg/m$^2$. The median for the 1945-1970 category is slightly higher at 8 kg/m$^2$, with both 1945-1970 and 1970-2000 categories displaying much smaller variability, despite 1970-2000 having more projects than the Before 1945 category.

Wood exhibits a median tMI of 5 kg/m$^2$ for buildings constructed before 1945, while the 1945-1970 and 1970-2000 categories both show a median of 2 kg/m$^2$.

Synthetic material is not prominently represented in transformation waste. Interestingly, the material is more present in buildings constructed before 1945.

Paper/cardboard displays considerable variation across construction years, with a median of 1.7 kg/m$^2$ for buildings constructed before 1945, 0.25 kg/m$^2$ for 1945-1970, and 0.5 kg/m$^2$ for 1970-2000.

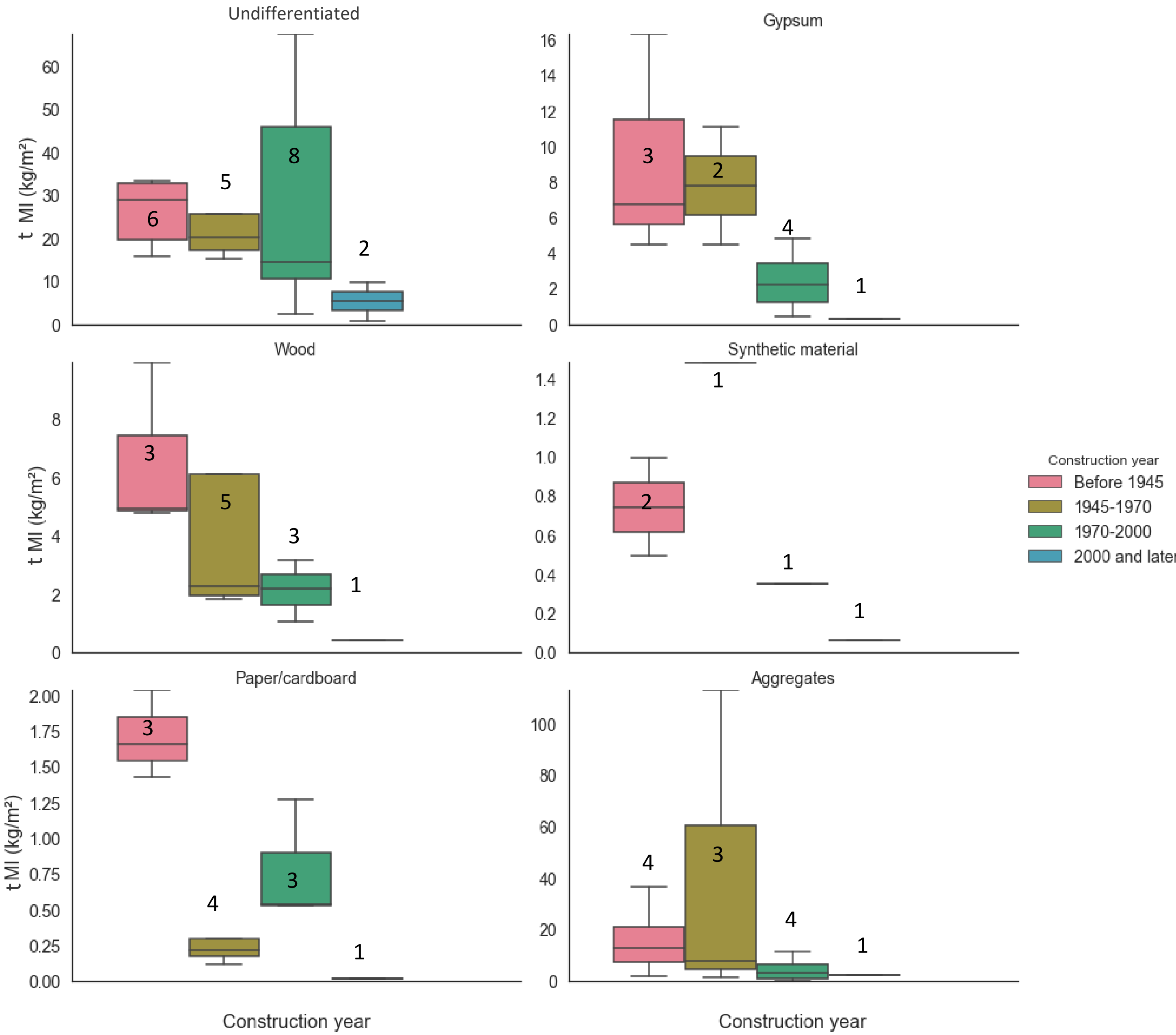


*Figure 4.10: Boxplots of tMI of transformation waste by material and construction year. The numbers represent the number of projects that make up the boxplot.*

Aggregates show a median tMI that is relatively consistent across construction years, ranging from 5 to 10 kg/m². However, the 1945-1970 category has an exceptionally high maximum value exceeding 100 kg/m², which significantly stretches the graph.

Five outliers are identified in the transformation projects per construction year. Three of these outliers are found in Undifferentiated, with the highest being 1000 kg/m² in the 1970-2000 category, another around 250 kg/m² in 1945-1970, and one around 50 kg/m², which is comparable to the maximum value for 1970-2000. Wood shows a single outlier for the 1945-1970 period at approximately 25 kg/m². Lastly, Paper/cardboard has an outlier at 0.5 kg/m$^2$ which is actually below the median for the 1970-2000 category.

### 4.3.3 Material intensities for wood per construction year and building type

Figure 4.11 illustrates the linear regression of the rMIs of wood by building type and construction year.

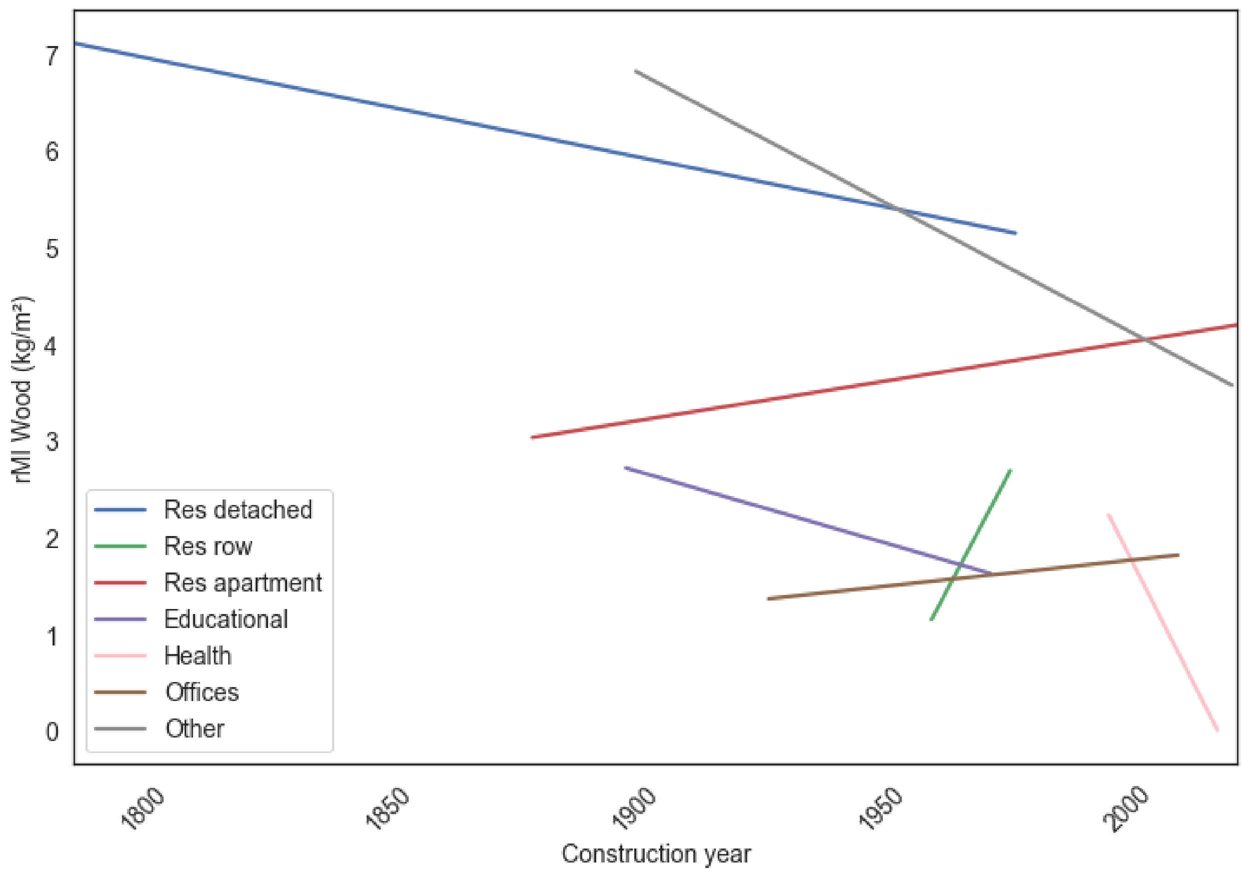


*Figure 4.11: Linear regression of rMIs of wood per building type and construction year.*

The figure shows that detached houses used to have the highest rMI (7 kg/m$^2$), but decreased over time. This is also the case for educational, health, and 'other' buildings, where 'other' starts on a similar rMI level but a hundred years later and drops to approximately 4 kg/m$^2$ in a hundred years. Row houses, apartments, and offices increase over time, not yet reaching the starting value of detached houses. Apartments and offices follow the same growth curve, where as row houses have a short steep increase of wood per square meter.

## 4.4 Recycling potential

Tables 4.1 and 4.2 show the total potential mass of recyclable materials from the projects studied.

The numbers have been rounded, due to the confidence of the scale as well as the applicability of the recycling rates to the renovation waste materials.

*Table 4.1: masses (kg) of potentially recycled content of renovation waste per material and building type.*

| Building type | Aggregates | Undifferentiated | Gypsum | Paper/cardboard | Synthetic material | Wood |
|---|---|---|---|---|---|---|
| Res detached | 40 000 | 290 000 | 3000 | 17 | 0 | 32 000 |
| Res row | 180 000 | 1 900 000 | 0 | 14 000 | 1500 | 69 000 |
| Res apartment | 240 000 | 2 600 000 | 80 000 | 58 000 | 6600 | 180 000 |
| Educational | 19 000 | 460 000 | 0 | 1100 | 290 | 13 000 |
| Health | 34 000 | 560 000 | 6000 | 2500 | 0 | 46 000 |
| Offices | 41 000 | 630 000 | 1000 | 4100 | 0 | 46 000 |
| Other | 23 000 | 630 000 | 8000 | 0 | 830 | 48 000 |

*Table 4.2: masses (kg) of potentially recycled content of transformation waste per material and building type.*

| Building type | Aggregates | Undifferentiated | Gypsum | Paper/cardboard | Synthetic material | Wood |
|---|---|---|---|---|---|---|
| Educational | 28 000 | 110 000 | 5000 | 2300 | 0 | 12 000 |
| Offices | 130 000 | 1 000 000 | 300 000 | 50 000 | 6700 | 130 000 |
| Other | 180 000 | 1 200 000 | 100 000 | 18 000 | 4900 | 110 000 |

# 5. Discussion

## 5.1 Interpretation of results

### 5.1.1 Skip research and Interviews

The skip research proved to be more difficult than I expected. This was partially caused by the diverse materials found which could be explained by the accessibility of a skip that is placed on the street. It is understandable that people who walk by, use the skip as a trashcan, even though this is not its purpose. It seems that there are not enough public trashcans for people to easily get rid of their garbage.

When comparing the waste generated from ‘small’ private renovations with the projects used to calculate the rMI and tMI, I only received information on the general material waste stream, but no information of any contamination. I can imagine that there is less contamination of the skips used during large renovation projects. The main reason for this would be that a fence might be placed at large projects (e.g., offices). This would prevent access to the skips by pedestrians, limiting the chance of polluting the waste stream.

Most people who need a skip for their renovation project rent a construction and demolition waste (CDW) type skip, as this type accepts a large range of materials. This type is more expensive to rent due to the intense sorting process after pickup. However, for the renter, it is more feasible than renting different skips as this will take up more space which is often limited in a neighborhood. It could also end up being more expensive in the long run, if one has to rent the skips for a longer time, since it takes longer for them to fill.

It is understandable that people also put household elements, e.g., furniture, fridge, matrasses, in the skip when renting one. Without a skip, these materials are brought to the thrift store when in reasonable condition, or to the recycling facility (Milieustraat) as domestic waste. This domestic waste and the Undifferentiated waste from the CDW skip are treated similarly at the waste treatment facility. Therefore, it is not necessarily a problem that these elements are put in this CDW skip. It only becomes a problem when it hinders the sorting process. For example, mattresses, due to their lightweight filling, can cause disruptions on the conveyor belt by being scattered by the wind, while e-waste, which contains valuable components, requires early separation to preserve its value and ensure efficient recycling. I also noticed that the skips are often filled higher than the allowed 30 cm above the rim which could lead to empty transportation as those skips are not safe to transport. As transportation negatively impacts the environment caused by the emissions, empty transportations need to be reduced as much as possible. Therefore, people who rent a skip need to be better informed of the limits of the CDW skip.

The fact that the municipality only has a limited knowledge of skip locations held back the start of my research. A reason for this limited knowledge could be that permits are only required for placement on paid parking areas and not for public space. Therefore, the majority of skip locations is unregistered, especially outside the historic city center. Renters neglecting to apply for a permit, or skips placed on private property are other possible reasons for unregistered locations. Unfortunately, there is no information on this ratio.

#### 5.1.1.1 Synthesis skip research and interviews

The skips rented for private renovations in combination with the results from the interviews provided a better understanding of the elements discarded during renovation, instead of the general material composition known from the dataset on large renovation projects.

The municipality could help prevent contaminations of skips in general by making sure there are enough trashcans available on the streets through spatial analysis. I also recommend future researchers to interview people from the practical workplace to understand the challenges around renovation waste. This could be approached systematically as part of the research, or more informal for personal growth.

### 5.1.2 Total material amount

It is remarkable that renovated apartments generated 3.6 kilotons of material out of 63 projects, whereas row houses generated 2.5 kilotons out of 79 projects (figures 4.3 and 4.4). This could be explained by the size of the project. One project on an apartment complex could include, e.g., 140 apartments, whereas one street of row houses contains, e.g., 26 houses. Therefore, the mass was divided by the total floor area of the project to correct for the number of dwellings in the project.

The presence of Paper/cardboard is difficult to explain. Namely, Paper/cardboard are expected to come from packaging. However, since this waste comes from newly placed elements, it falls under construction waste, which is tracked separately of renovation waste. It could be interesting to research the origin of the Paper/cardboard waste as this is a well recyclable material.

Additionally, the 21 transformation projects studied generated a similar magnitude of waste to the 282 renovation projects. It seems that a transformation project generates a substantial amount of waste thereby affecting the building much more than a renovation project (see also section 5.1.3.2).

Renovation waste shows an increase for more recent construction years, which is most likely connected to the number of projects that make up the graph (figures 4.5 and 4.6). Transformation waste per construction year shows a large contribution of Gypsum in the Before 1945 category. It is unclear why the more recent construction years have much less Gypsum as the number of projects lie close together.

### 5.1.3 Material Intensity calculation

#### 5.1.3.1 General observations

Among the waste streams, Undifferentiated and Aggregates emerge as the most consistent, appearing across all building types and consistently exhibiting the highest r,tMI values. This is likely due to their high density, which significantly contributes to the total waste generated (Gontia et al., 2018). In contrast, gypsum and synthetic materials are less represented in the data, despite their expected prevalence in renovation activities (Sun et al., 2020).

The distance from the minimum/maximum to the median of the renovation projects categorized by building type is also interesting. I expected less variation for building types with fewer projects, however, this is not consistent with observations. For example, wood shows much more variance for detached houses with seven projects, than row houses with 14 projects. Also, aggregates in educational buildings is made up of only four projects but shows more variability than apartments with 19 projects.

A general reason for a low rMI and tMI could be that the project only used one skip per material. This occurred at least four times in the data. Since I added up the mass of the skips per material type per project, the mass remains low. It seems that the projects with just one skip might be a mistake. Maybe more skips were needed, or the project number was renewed even though it was part of an already existing project. At least one description mentioned the renovation of 192 apartments, whilst only one skip for the full project was needed. In this case, exclusion due to the scope was not a viable explanation as the skip was used in March 2022.

It should also be considered that not every skip is filled to the rim. At the end of the project, there might not be enough waste for the skip to be full, or a specific material was scarcely generated. Furthermore, it is possible that skips are filled more than the allowed height. We know this happens from the skip research, which was a reason to not calculate the material intensity by dividing the mass per skip by the floor area of the project, but to instead use the full project. For any project with several addresses, I corrected this by dividing by the total area of all the addresses.

#### 5.1.3.2 Renovation vs. Transformation

The material intensity values observed in transformation projects per building type are generally higher than those in renovation projects, a difference attributable to the more intensive nature of practices involved in transformation processes (Leskovar & Premrov, 2019). When imagining a building transformation, I imagine a building getting stripped to the underlying structure and then built back up again to fulfill the new needs of the building. For example, transforming an office into apartments. The meeting rooms from the office might be too small to reuse as rooms, and the walls need to be moved. Contrarily, a renovation of a detached or row house often consists of just a kitchen and bathroom renewal. Since these only cover a part of the total floor area, the rMI is logically lower than a tMI from a full transformation.

Looking at the variability of renovation and transformation MIs per building type, the third quartile for transformation is less far from the median than for renovation. For transformations, this can be explained by the number of projects creating the graph. Namely, with less than four projects, the quartiles of the boxplots are just being placed between the minimum/maximum value and the median. The quartiles are not evenly distributed for rMI. This could have to do with a higher chance of outliers when having more projects. Since renovation can be performed at different intensity levels (e.g., improvement of energy efficiency or a complete home renovation), this could lead to the variabilities around the median of renovation.

Transformation projects predominantly focus on converting office spaces into apartments, with transformations starting as residential buildings being absent in this data. This observation aligns with current trends in urban development, where the repurposing of office spaces to meet housing demands has become increasingly common (Itard & Klunder, 2007).

#### 5.1.3.3 Renovation type

Next to only kitchen and bathroom renovation, there are of course also projects where, for example, a detached house is completely renewed, leaving only the frame. I can see this renovation intensity being more common in a detached house than in a row house, probably because there is more freedom as there are no shared walls/direct neighbors. Also, I can imagine the house structure providing more freedom as there is often more space and the layout is less strict. An example of this is a farmhouse with a lot of small rooms, which are removed and replaced with a large living area. This could explain the higher end values of the boxplot of detached houses. The lower end could be explained by a farmhouse that already had an open space living area. I can imagine that this renovation would be more similar to a row house renovation, where the work includes updating the window frames, kitchen/bathroom, maybe the stairs, painting, et cetera, leading to less waste mass production. This could explain the minimum values between 0 and 2 kg/m$^2$.

#### 5.1.3.4 Construction year trend

For renovation, the total mass distribution (see figure 4.5) can be explained by the number of projects in each category. Most material has come from the 1970-2000 category, where Undifferentiated also has the highest share compared to the other categories. For transformation, the mass distribution does not follow this trend, as Before 1945 and 1970-2000 both have more projects than 1945-1970 but are lower in total mass. Also prominent is the large share of gypsum Before 1945, which is of a similar size as Undifferentiated. Transformation has only been done on 2 projects from 2000 and later, providing very little mass per project.

When examining rMI and tMI across different construction year categories, a notable trend emerges (see figures 5.1 and 5.2). Namely, transformation projects show a decreasing tMI median value in more recent construction years. This trend is not observed in renovation projects, where rMI median values do not follow a consistent pattern and, in the case of Aggregates and Gypsum, even increase over time. This suggests that more recent buildings are either designed with more efficient material use or that transformation practices have evolved to be less material-intensive over time. Another explanation could be a more modular approach towards the construction of the building, leading to easier reuse directly from the transformation site, instead of the materials being put in the skip as waste. The reuse of velux windows is a small example of this modular approach. Additionally, I suspect that for educational buildings and offices, for example, the owners invest in sturdy materials as the elements (e.g., doors) are used intensely day in and day out, whereas the lifetime of dwellings might be shorter due to the difference in demand. When taking into account the esthetic value of the living environment for dwellings, it is likely that building elements are being replaced long before the lifetime of the element has passed. In contrast, educational buildings and offices are more likely only renovated when there is a change of command, renewed guidelines, or a desperate need. For example, the civil engineering building at TU Delft still has single glazed windows in the study area, as these still fulfill their function and there is no urgency for replacement.

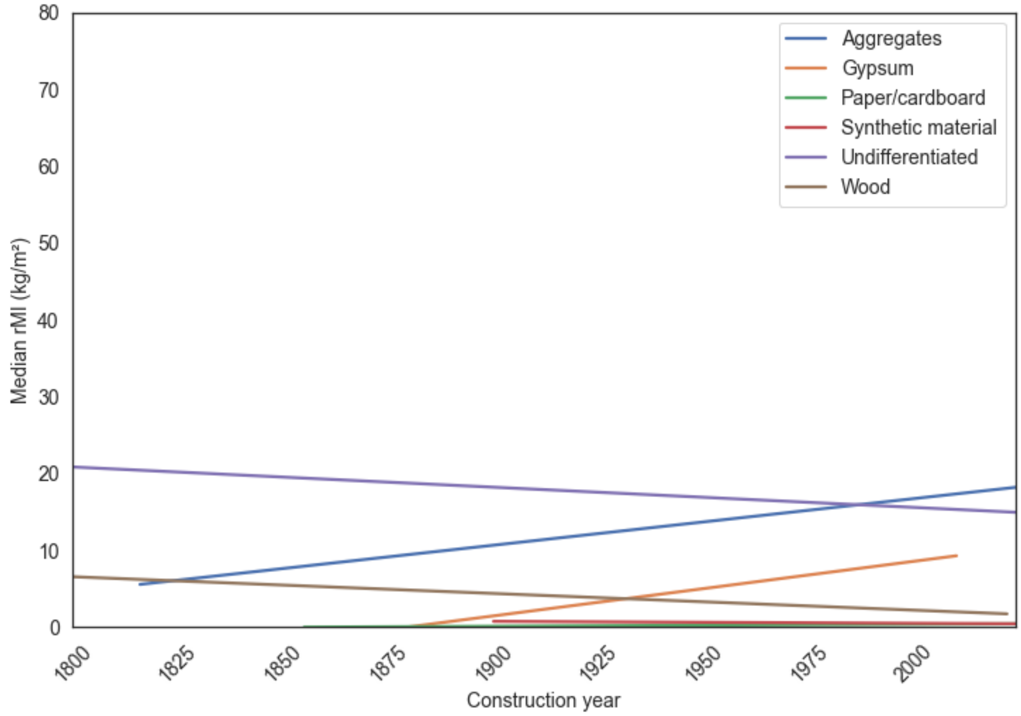


*Figure 5.1: linear regression on rMI median per construction year.*

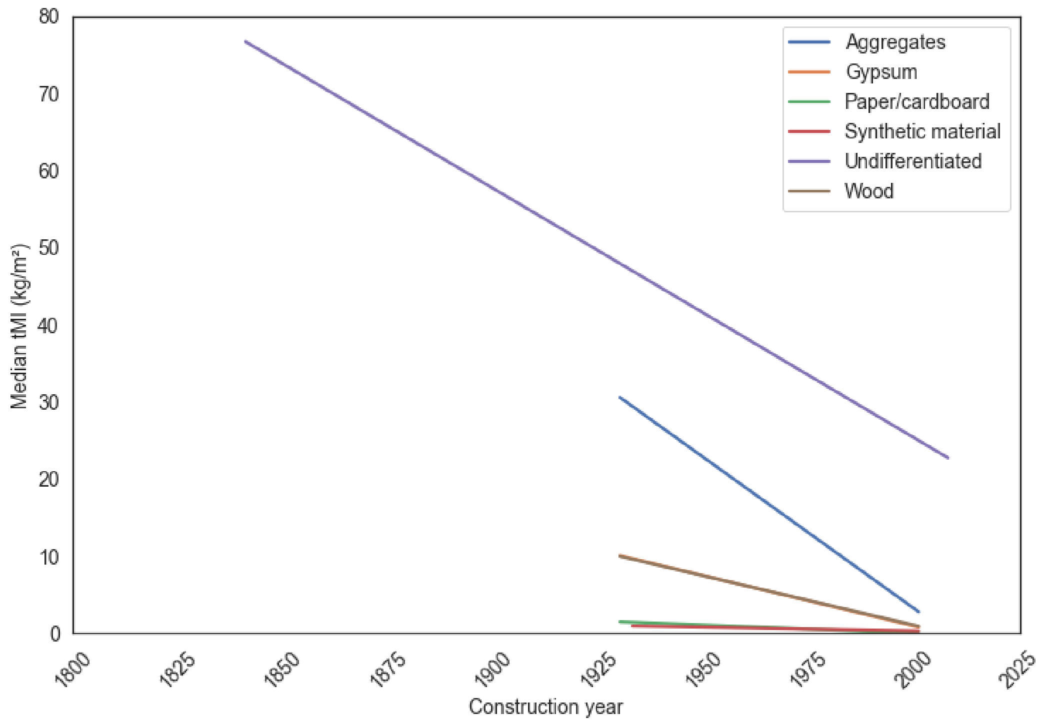


*Figure 5.2: linear regression on  tMI median per construction year.*

#### 5.1.3.5 Building type

Educational buildings and offices are often large buildings where I would expect more public parking spaces. When the building is transformed, it is not in use, creating space for the different skip types to be placed. However, during renovation of an office, educational building, or dwelling, the building could still be in use, limiting number and types of skips, and therefore the separation options, as parking areas are occupied by the users. Parking space is often scarce in the Netherlands, especially in urban neighborhoods where a substantial part of the renovation for school and dwellings take place. This limits the options to place all the different skip types and therefore the thorough separation of the materials. This could lead to the more intense use of the CDW skip, as this skip type accepts the most diverse input. However, the results show that this only applies to detached houses.

Another explanation for the difference in rMI of Undifferentiated between the different building types could be that projects on detached houses generate less waste. They are often single standing projects, as opposed to systematically renovated row houses and apartments. This could mean that the CDW type skip is more important for detached houses, as renting multiple skip types could be more costly in the long run. This difference in approach could explain the difference in rMIs between detached houses, and row houses and apartments.

#### 5.1.3.6 Wood

It seems that wood became a less frequent building material for detached houses, educational, and 'other' buildings as the wood waste generated decreases over the years (see figure 4.11). It might have been replaced by for example by synthetic materials or concrete. The increase in rMIs of apartments, offices and row houses could be related to the increase of construction of those building types, especially the typical 1970s row houses. Unfortunately, I was not able to find a more specific explanation.

The different starting points of the different building types can be explained by the limited projects available. Therefore, more datapoints could provide a more holistic understanding of the wood per building type and construction year distribution.

#### 5.1.3.7 Synthesis r,tMIs

The boxplots (figures 4.7 - 4.10) are a good representation of the rMIs and tMIs as the distribution of the calculated rMIs and tMIs is visible. The median is appropriate for rMI and tMI determination as the median is less affected by outliers than the mean, and the minimum and maximum show the variability of the calculation. The results show that the building type has a large impact on the rMI, whereas construction year has less effect. However, transformation projects are affected by the construction year, decreasing in tMI for more recent construction years. When applying the results, it should be kept in mind that categories with limited projects are less reliable and should be handled with care. Lastly, Gypsum and Synthetic material not only show low rMI values, but are not even properly represented by the number of projects. I would recommend to further investigate this, as these are common building materials. I would also recommend to increase the number of datapoints by reaching out to more renovation companies to increase the confidence of the results; to investigate the possibility of using a separated

Undifferentiated waste stream in the r,tMI calculation, for which a good connection with the waste treatment company is needed as they would need to keep track of the separation processes per skip. An example of such an overview can be found in table B.1.4 of Appendix B. However, as this information was provided only by Prezero, I assumed it was not directly applicable to the other waste treatment companies, as there might be a different focus regarding renovation types.

This research showed the potential of analyzing the waste generated per building type across construction years. Future research could expand this by adding more datapoints to investigate the specific change in waste generated in connection to the building type and construction year instead.

### 5.1.4 Recycling rates

During the interviews with the waste treatment facilities, they mentioned that their recycling rates are good, however, I have my doubts on the correctness of the End-of-Life Recycling Rate (EOL RR) determination. For example, Aggregates is a material that does not lose its properties. When crushed to gravel, it can be reused to make concrete or other building materials. The percentage of used material that can be reused in the production of building material is the limiting factor. Therefore, it seems that the EOL RR of Aggregates might be too low while in reality it might be more similar to the Maximum Recycled Content (MRC) (the percentage of recycled material in a product). The opposite applies for Wood. Namely, wood is often replaced when it is rotting or no longer a stable building material. The 0.76 EOL RR is probably reached by incorporating the recycling of the wood into chipboards. However, as chipped wood can never fulfill the same function as the, e.g., wooden beam did before, it is called downcycling and should not be used for making up the EOL RR. The Undifferentiated waste stream also follows this pattern as the 0.95 EOL RR is most likely achieved by the downcycling of the materials to road filling (Hu et al., 2013). The EOL RR for synthetic material seems reasonable, given the ongoing challenges in recycling synthetic materials due to their complex composition. The EOL RR for Paper/cardboard also seems reasonable due to the long-established high recycling rate (PRN, 2024).

#### 5.1.4.1 Synthesis recycling rates

It seems that the EOL RR alone does not represent the chances of recycling a material properly, as downcycling is often included. Therefore, the potential mass of recycled material should be approached with consideration. It might be interesting to research if the EOL RR of renovation waste is indeed similar to that of demolition waste. Also, the total mass calculated in this research is based on a selection of buildings in the Netherlands and is therefore not representable of the total mass generated by the Netherlands. I would recommend expanding the geographical to include all buildings in the Netherlands to obtain the potential mass of reusable renovation waste.

### 5.1.5 Unstudied waste materials

In this study, only two projects utilized a skip specifically for asbestos-containing material. However, external information from a project website (which was not part of these two) indicated that asbestos was also removed during renovation of other projects (Van Wijnen, 2024). This discrepancy suggests that asbestos is likely underreported or inadequately tracked in the data, particularly for buildings constructed during the peak years of asbestos use. Given the historical use of asbestos, especially before its widespread regulation and removal initiatives, it is reasonable to expect its presence in many older buildings undergoing renovation. The lack of data on asbestos might also be due to its specialized handling, which could lead to it being treated by other companies than the general renovation waste stream.

Metal waste was found to be relatively low in mass, which can be attributed to the fact that many Dutch buildings are constructed with reinforced concrete frames that are often left unchanged during renovation. The recorded metal waste likely originates from smaller sources such as the replacement of wiring or minor fixtures. Another reason could be that the metals are brought directly to recycling as money can be gained from this. Given that e-waste is managed through a separate, dedicated waste treatment process, it's clear that metal from larger structural components or appliances is not included in the waste streams analyzed here. This contrasts with demolition waste studies, where metal is more prominent due to the complete teardown of structures, including the extraction of structural steel and other significant metal components (Sprecher et al., 2022).

Glass waste was unfortunately too low in quantity to allow for meaningful analysis in this study. This was surprising, as window replacements are common during renovations, particularly in efforts to improve energy efficiency through better insulation (Sun et al., 2020). It could have to do with the relatively small surface area of a window compared with the façade. A bottom-up approach could confirm this reasoning.

Hazardous materials were barely found during the projects, and it is unclear what it consists of.

Insulation was also surprisingly absent from the dataset, even though it was expected to be present in a large number of projects given the current emphasis on improving building energy efficiency. The absence of recorded insulation waste could be due to insulation being left in place during renovations, either because it remains effective or is supplemented rather than replaced. It is also possible that newer insulation materials are simply less dense and therefore contribute less to the overall waste mass, making their presence less noticeable in the data.

Roof waste, it is unclear why it is managed distinctly from other types of waste. One possibility is that roofing materials, such as tiles, may have specific recycling processes that make them easier to handle when separated from other waste types. However, further investigation would be needed to confirm the rationale behind this categorization.

The small proportion of waste falling into the Other materials category is a positive indicator for recycling efforts. It suggests that most materials are being sorted and categorized correctly, leading to more effective recycling and resource recovery.

#### 5.1.4.1 Synthesis unstudied waste materials

During the large renovation and transformation projects, limited amounts of Asbestos-containing material, Metal, Glass, Hazardous material, Insulation material, Roof waste, and Other was found. When comparing this to the findings of the skip research, I expected more presence of those materials regarding the number of projects. It is understandable that the material not always contributes a lot by mass (e.g., insulation material), but is expected to contribute to a higher number of projects. As I was not able to find a reasonable explanation for this observation, more data on renovated buildings in the Netherlands could help prove the absence of these materials or the low mass contribution.

## 5.2 Limitations and Recommendations

### 5.2.1 Observational bias

The data covers a diverse range of renovation and transformation types, which I feel represent the most typical projects done in the Netherlands when comparing to the definition of Leskovar & Premrov (2019).

The data tells me that there is a large variation in the number of skips needed for a project. It could be a difference of several dozen to just a single skip for a project. When using this next to each other, it's unclear if the data came from projects where little material came out (e.g., energy efficiency improvement where you can expect more material being put in (van Oorschot et al., 2023)) or if the building has an extremely large surface area, such as the hospitals.

The data did not clearly present the specific floor area of each project. This could have led to over- or underestimation of the floor area. This is visible in the Health building type, where I used the floor area of the entire building (often hospitals) which are very large compared to the other building types.

There is a sample bias based on the number of renovation projects (281) and transformation projects (21). It seems that renovation projects are more common than transformation projects. To be sure, all renovation/transformation projects in the Netherlands in a certain time period need to be counted.

Lastly, I used the data as provided by the one company, however, the materials are collected by different waste treatment companies and aggregated by Van Wijnen. Since every scale has a different confidence, this could have led to a measuring bias leading to a deviation between the masses that is currently not accounted for.

### 5.2.2 Skip research and Interviews

For an investigation using skips, a better connection with the skip renter and the company is needed. A citizen science project could provide the insights I was looking for, as more people would participate in the research. For example, when renting the skip, the renovators could write down the dimensions and the type of materials they put in the skip on a template provided by the researcher; the skip company or the researcher can then calculate the mass using the average density of the different materials. I would recommend for the researcher to conduct interviews with the renovation company, as well as contractors and participants to gain the knowledge to generate a good template.

### 5.2.3 Data

There were limitations in the data that impacted the scope of this research. Not all the data I acquired could be utilized, largely due to missing information, such as the project location or the number of apartments involved.

Additionally, not all projects produce the same types of materials, and as a result, they do not require all the different types of skips for waste collection. This variability complicates the study of smaller, less common waste streams, which may be underrepresented in the available data.

Moreover, the data primarily pertains to relatively large renovation and transformation projects. However, it is important to note that renovation by individual homeowners is also a common practice in the Netherlands. Unfortunately, no quantitative information on waste generation from these smaller-scale renovations was found during this study. Capturing the waste generation from such projects may require a different research approach, tailored to the unique characteristics and scale of homeowner-led renovations.

The dataset included three negative values. All three negative values were Undifferentiated flows of which two belonged to a transformation project from ‘other’ to educational (-6440 kg and -3140 kg), and one a transformation from office to apartments (-257 kg). Including these values would have led to a smaller total mass and therefore also a smaller tMI. These negative values likely arose from different sources, such as error settlements or simple data entry mistakes, highlighting the need for careful data validation in future studies.

Lastly, including more data points in future studies could provide greater insights into materials that were not extensively covered in this research. Such an expansion could help strengthen the reliability of the results and provide a more comprehensive understanding of renovation waste flows. However, there is also the possibility that increasing the dataset introduces greater variability. Therefore, a proper analysis including testing the significance could increase the confidence of the results.

### 5.2.4 Validation

A significant challenge in validating the findings of this research lies in the limited availability of comparable studies. Most existing research on material intensity focuses on the total building stock, particularly what becomes available during demolition, concentrating on concrete, steel, and brick (Gontia et al., 2018; Heeren & Hellweg, 2019; Marinova et al., 2020; Müller, 2006; Ortlepp et al., 2018). The r,tMIs of the materials reported in these studies are generally an order of magnitude higher than those observed in this research This could be explained by the large mass of structures which are accounted for in demolition, but not in renovation. The wood r,tMI values found in this study align most closely with those reported by Deetman et al. (2020), although their work focuses on global data, which encompasses a broader range of building types and conditions. This could suggest that in the Netherlands, wood is mostly used for the Space plan and Skin layers of the building, which are replaced during renovation and that wood is not used in the deeper construction frame of the building. This makes the MI and r,tMI comparable for Wood, but not for materials such as concrete and steel which are embedded in the structure and remain untouched during renovation/transformation. As there is similarity between the MI and r,tMIs of Wood, it could also be expected for other materials that are used in the Space plan, Services, and Skin layers, like Gypsum or Synthetic material. However, little notion of these materials is found in demolition literature, probably because their mass is extremely low compared to concrete and steel, or that the demolition scope starts only after the building has been stripped of its Space plan, Services, and Skin layer.

The study by Sun et al. (2020), which is one of the few that examines decoration and renovation waste, includes materials such as gypsum, paper, glass, and metal. However, because Sun's research emphasizes the total material streams in mass, it does not allow for a direct comparison with the renovation and transformation MI values (in kg/$m^2$) presented here. They focused on this total material flow to get insight into their waste generation and treatment, as their waste treatment is not as sophisticated as the Dutch system, leaving the city with complications of waste disposal.

### 5.2.5 Temporal scope

I lack information on the duration materials remain at the waste treatment facility. The data only confirms that the materials were collected between January 2021 and May 2024. It is common in Material Flow Analysis (MFA) studies, which often incorporate MI, to use a year as a reference point for in-and-out flows (Condeixa et al., 2017).

Since part of this dataset relies on information from 2021 and 2022, the impact of COVID-19 on the number of projects undertaken by the company could be a factor. However, this effect is considered limited, as the analysis focused on individual projects rather than the total number of projects across the Netherlands, which would likely have been more significantly affected by the pandemic. Another aspect of the impact of COVID-19 is potentially the execution of ‘easier’ projects in case of another lockdown. This could have influenced the types and amounts of certain materials observed.

Developing an MFA for the entire renovation system could provide valuable insights into the annual input and availability of materials. Extending this to a dynamic MFA could further enable predictions or estimations of future renovation waste flows, offering a more comprehensive understanding of material use and reuse over time.

#### 5.2.5.1 Construction year categorization

The construction year categorization was based on the material changes mentioned by Metabolic (2020). However, other categorization methods could also be relevant depending on the research focus. For instance, the Tabula project categorizes buildings based on construction type, with an emphasis on energy usage (Tabula, 2017). This approach could be particularly useful for studies examining the impact of renovation on the energy efficiency of buildings, offering a different perspective that might reveal trends related to energy-saving practices.

An interesting observation from the data is that many buildings constructed between 1970 and 1980 are currently undergoing renovations. This trend suggests that these buildings are reaching a point in their lifecycle where renovation becomes necessary. With this knowledge, it would be beneficial to develop future scenarios based on building types and construction years to better estimate the volume and types of materials that will be available for recycling or disposal in the coming years.

In this study, I did not distinguish between buildings constructed before 1945, although significant differences in material use can be expected within this category. Buildings from Before 1945 can vary widely in their construction techniques and materials, especially if they are considered historical or monumental. A targeted study focusing on the renovation and restoration of older buildings could provide valuable insights into the specific waste streams generated by such projects.

The absence of transformation projects in certain construction year categories highlights the need for more data points. A larger dataset could increase the likelihood of capturing transformation projects across all construction year categories, allowing a more comprehensive analysis. The lack of data in certain categories limits the ability to make conclusive statements about trends or to compare transformations across different periods effectively. Therefore, expanding the dataset in future research could help fill these gaps and provide a more complete picture of material use and waste generation in the built environment.

### 5.2.6 Building types

In this thesis, the focus was narrowed to specific building types, although more categories could have been considered. For example, semi-detached buildings were included as row houses. Given that there were only 14 projects partially involving semi-detached buildings and considering that they represent only 8% of all residential buildings in the Netherlands, this approach seems reasonable (Ebrahimigharehbaghi et al., 2020). This contrasts with the approach taken by van Oorschot et al. (2023), who categorized semi-detached houses under detached houses. Her decision was informed by MI values reported by Metabolic, where semi-detached houses were found to be closer in MI values to detached houses rather than row houses (Metabolic, 2020).

However, separating semi-detached buildings could potentially affect the rMI values of row houses in this research, since semi-detached houses were found to be slightly larger than row houses. Despite this, I used specific floor areas for each project, which would mitigate any discrepancies. If semi-detached buildings had more waste, it would have been divided by a higher floor area. This reinforces the decision to use specific rather than average floor areas, as it minimizes potential bias. While it is unfortunate that the specific rMI values for semi-detached buildings are not available now, this could easily be addressed by adding an extra column in the dataset where building types, construction years, and floor areas are recorded.

The potential impact of not distinguishing between different apartment types, such as high-rise, gallery flats, or maisonettes, is also expected to be minimal. The primary differences between low-rise and high-rise buildings are found in the foundation, which contributes significantly to the mass during demolition (Sprecher et al., 2022). Since foundations are typically not altered during renovation, the difference in rMI values between these apartment types is likely negligible. Additionally, I decided to categorize aided living facilities under apartments. This decision was based on the observation that, although the buildings might resemble detached houses, they are structured with individual rooms akin to apartments. While this categorization is debatable, it was deemed appropriate not to classify them under Health, as aided living facilities differ significantly in construction from hospitals (which was the most common in the Health category). The type of care provided could influence the materials found in these facilities, but upon reviewing the projects, it was clear that these buildings are not heavily equipped with hospital-like medical equipment. Ideally, aided living facilities would have their own category, but this is challenging given the diversity in building styles (some are more detached-style, while others resemble low-rise buildings).

The ‘other’ category could also be refined by splitting into more specific types, e.g., commercial, industrial, et cetera. Additionally, future research could consider adding more detailed specifications for each building type, such as distinguishing between wooden, concrete, or other construction types (Gontia et al., 2018). However, it remains to be seen if these construction types are actually present in the Netherlands and if the differences affect the renovation waste flows, as the structure of a building usually remains the same (Brand, 1994).

Lastly, the buildings analyzed in this project represent only a portion of the total building stock in the Netherlands. The proportion of these projects compared to the total number of renovation projects across the country is currently unknown. However, the BAG dataset contains valuable information on buildings that have applied for a renovation ("verbouw") permit. This dataset could potentially be utilized to estimate the total renovation waste flow for the Netherlands or even a specific region, depending on the focus or objectives of the research.

### 5.2.7 Renovation types

In general, transformation projects exhibited less variability in tMI compared to renovation projects rMIs. This difference could be attributed to the nature of transformation, where more of the building is improved or repaired, often involving more extensive work on the building's core structure (including components like the building’s skin and space plan (Brand, 1994). This uniformity in the scope of work could lead to more consistency across transformation projects, unlike renovations, which can vary significantly in scope—from a simple kitchen update to major energy efficiency improvements. The more consistent traits of transformation projects might make them more predictable in terms of material waste.

Additionally, higher walls are often associated with buildings undergoing transformation, as these are usually offices or educational buildings. This might also be a reason to treat transformation separately from renovations. Understanding these differences better could help clarify why material intensity variability differs between transformation and renovation projects.

It would be valuable to further explore different types of renovation projects, as focusing solely on the overall comparison between renovation and transformation might overlook important distinctions within renovation practices themselves. For example, kitchen renovations typically affect a smaller area of the building, yet in this study, the material intensity was calculated using the floor area of the entire building. This approach could be refined in future research by categorizing renovations by type, or by adjusting the floor area calculations accordingly.

### 5.2.8 Floor area

In the context of this study, the choice of data sources and methodologies for determining floor areas and construction years was influenced by several practical considerations. Selecting the specific projects from the BAG3D data set while keeping in mind the different floor areas of the buildings within a project, proved extremely difficult (Esri Nederland, 2024). Also, the appropriate material to run the size of this data set was unavailable for my research. Despite the limitations of the BAG3D dataset, the BAG Viewer provided up-to-date and manually accessible data, facilitating the analysis (Kadaster, 2018).

To determine the floor areas of buildings, I opted to use a data layer that directly provided these figures rather than relying on proxies or assumptions based on the number of floors and building height. This approach minimized the need for additional assumptions, such as estimating floor heights, which could introduce inaccuracies.

However, there were some challenges and limitations in the data:

- **Underestimation of Floor Area for Apartments**: For apartment buildings, the provided floor area sometimes only included the individual apartment spaces and excluded shared areas such as hallways and communal spaces. This could result in an underestimation of the total floor area, potentially skewing the rMI values for such buildings.
- **Proxies for Floor Area**: In cases where the exact location or detailed floor area information was unavailable, a median value or proxy was used. While this approach aimed to mitigate the influence of unusually large floor areas, it could still lead to some degree of overestimation or underestimation.
- **Façade Renewal Projects**: Projects focusing solely on façade renewal often lacked information on the number of apartments, making it challenging to determine the total floor area. These projects were mainly excluded from the r,tMI calculations, as the floor area of the building was unknown. Including them could have potentially resulted in lower r,tMI values, since the façade's mass would be divided by the building's total floor area.
- **Transformation Projects**: For transformation projects, there was an attempt to use the floor area of the building before transformation. However, with the updating of datasets, historical data on the former floor area was often lost. As a result, the floor area of the transformed building was used as a proxy, assuming it to be similar to the former area. Since in practice the floor area could have been larger or smaller, the effect on the tMIs is unknown.
- **Hospitals**: Determining the appropriate floor area for hospitals proved difficult. The entire floor area of the hospital was used for analysis, but it would be more accurate to focus on the area undergoing renovation.

### 5.2.9 Synthesis limitations and recommendations

When using the results of this research, be aware of the potential bias caused by the different number of projects between renovation and transformation projects. The skip research and interviews were a good start to get insights in the real life problems that occur during renovation and waste treatment. A citizen science project could generate enough information to use this real-life information. It is also worth looking into a redesign of the skips that would allow for better separation of the material types, whilst requiring less space.

Be aware that results from this thesis can not be used directly for Material flow Analysis (MFA) as the temporal scope is not limited to one year as is common in MFA studies, and the data does not cover all buildings in the Netherlands. Also, keep in mind that the building types were aggregated into fewer categories. Including more datapoints could provide the possibility to research more different building types and potentially different renovation types as there is still a research gap here. For this to be successful, more specific information from the renovation company is needed; combining this with a request for specific floor areas per projects could elevate the quality of the findings.

## 5.3 Societal relevance

Calculating the amount of renovation waste and obtaining insights into the type of waste is of societal relevance for several reasons. First, it helps municipalities to work towards their target of 100% circular construction sector (Gemeente Leiden, 2022). At a national level, the government obtains insights into the status of renovation waste, although it is difficult to compare with other countries due to limited data there as well. However, having this knowledge could encourage other nations to prioritize and expand research in this area, fostering a more comprehensive understanding of renovation waste across borders.

Second, the knowledge on renovation waste generated per square meter helps estimate the future renovation waste generation by multiplying the r,tMI with the specific floor area. This allows for a better estimation of the number and types of skips needed for a renovation project by the contractor, renovation company or private renter. It also allows the waste treatment companies to better plan their waste collection, transportation, and processing, thereby reducing costs and improving the efficiency of waste management systems.

Third, by quantifying renovation waste through a citizen science organized by researchers and, e.g., the municipality, residents can be made more aware of the scale of waste production. This could lead to a stronger understanding of sustainable practices, such as the reuse of building elements or a reduced importance of esthetics, which prevents early replacement before the end-of-life. The research also shows that proper material separation at the forefront of renovation waste generation is important to increase the chances of recycling. This is crucial in reducing the environmental impact of construction activities, which are major contributors to landfill waste and greenhouse gas emissions (Huuhka et al., 2023).

## 5.4 Industrial Ecology relevance

This research adds to the field of Industrial Ecology (IE) by expanding the knowledge on materials flowing through the building sector, tackling part of the research gap on renovation waste. By combining skip research, interviews, and material intensity MI type calculations, a method commonly used in Material

Flow Analysis (MFA), this research had a broad approach to renovation waste. Working with information from skips used during renovation is especially unique as this was thus far only used for demolition projects Sprecher et al. (2022). This so-called top-down method helped to gain insights into the mass of waste generated per square meter of renovation and transformation projects on dwellings, educational and health buildings, offices, and 'other'. The renovation and transformation material intensities (r,tMI) from this research can be used next to the already existing MIs on demolition to fill the gap of the use phase of a building as this was often neglected in MI determination for full demolition. Since the field of IE is focused on optimizing resource use and minimizing environmental impacts across industrial systems, the chance for recycling renovation waste increases when there is a better insight into the type and amount of it.

## 5.5 Future research

In addition to the recommendations provided earlier, future research could benefit from adopting a bottom-up approach by closely tracking specific renovation projects. For this to be effective, construction workers need to meticulously track the materials they remove and/or a citizen science project where private renters track their waste has to be implemented. This approach could be paired with a Life Cycle Assessment (LCA) to examine the environmental impacts associated with the different waste materials. It would be particularly insightful to investigate whether early separation of materials is genuinely more environmentally friendly than bulk collection followed by separation at waste treatment facilities.

A further development of the bottom-up approach would be to connect the information to the material passport for buildings. These passports would then identify renovation possibilities in advance, or at least before the renovation begins. Such an initiative would provide a more accurate overview of the materials within a building, help estimate when these materials will become available, and indicate if the materials from that building are actually suitable for reuse and recycling. This approach was already investigated by Sesana et al. (2020) and Sesana & Salvalai (2018) for non-residential buildings, but could be explored further by incorporating residential buildings and specifying between renovation and transformation. Additionally, establishing an MFA for renovation waste across the Netherlands could greatly enhance our understanding of how materials are distributed and how long they remain in use. A more advanced step would be developing a dynamic MFA to forecast future renovation waste flows, though acquiring the necessary data for such an analysis might be challenging.

Finally, rather than solely relying on MI measured in $kg/m^2$ for renovation and transformation, it could be beneficial to develop a renovation and transformation mass percentage per material. This number would represent the proportion of each material present in a building that will be removed during renovation. To calculate this percentage, you would need to divide the amount of waste taken out during renovation of a specific material by the total stock of that material in the building.

The bottom-up approach, material passport, and an MI mass percentage are potential future research options, depending on the objectives.

# 6. Conclusion

This research provides a broad view on renovation waste by the combination of a skip research via fieldwork, interviews, and material intensity calculations applied to renovation and transformation projects in the Netherlands. The use of skip data to quantify renovation and transformation waste is groundbreaking, as research up until now mostly focuses on quantifying demolition waste and is often determined using a bottom-up approach.

The findings from the skip research reveal a diverse range of materials present in renovation waste, providing more detailed insights than the data obtained from the renovation company Van Wijnen. The research also highlights that skip renters take advantage of the broad range of materials accepted in the CDW type skip. The interviews revealed both the knowledge and the knowledge gaps of contractors, renovation companies, and waste treatment companies and helped me understand the struggles regarding renovation waste management.

The renovation and transformation material intensities (r,tMIs) were calculated for each material across various building types (detached houses, row houses, apartments, educational, health, offices, and ‘other’) and construction years (Before 1945, 1945-1970, 1970-2000, and 2000 and later). The results of each renovation material show a large variation between the different building types but little variation between the different construction years, suggesting that building type is a critical factor in calculating rMIs. Future research could expand the building categories to refine these calculations further. For transformation projects, the construction year is a key factor, showing a decrease in tMI for newer buildings.

The Undifferentiated waste stream plays a major role in renovation and transformation waste. Since this waste stream is a mix of all the other materials, separating this stream could unlock valuable insights into its composition and contribution to renovation waste. Aggregates are also consistently present across all building types, while Gypsum and Synthetic material are the least represented, both in number and mass.

Among renovation projects, apartments emerge as the most prevalent building type, generating all the materials studied. Transformation projects, however, are only represented by educational, offices and ‘other’ buildings. In general, tMI median values are higher than renovation rMI median values, which can be explained by the intense nature of a transformation.

Expanding the dataset in future studies could improve the confidence of the r,tMIs and allow for a more in-depth analysis of less-represented materials, providing a fuller understanding of renovation waste generation in the built environment. The findings contribute to a deeper understanding of the material flows in renovation and transformation practices, laying the groundwork for more sustainable waste management strategies in the built environment. This research therefore directly supports the goal of enhancing material reuse and recycling within the circular economy.

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# Appendix A

## 1. Skip locations

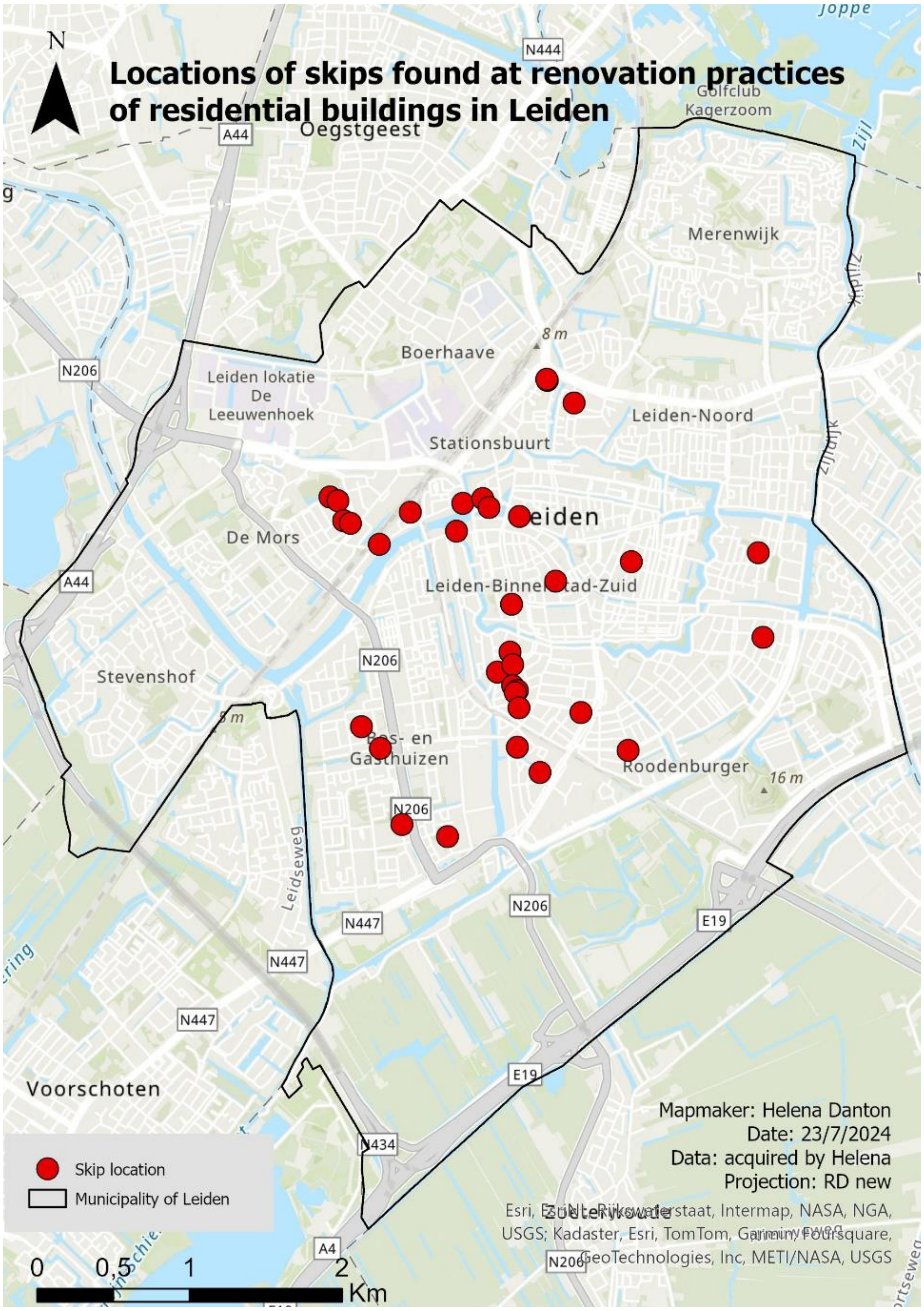


*Figure A.1.1: map of skip locations found in Leiden during 2 cycling sessions of an hour.*

# 2. Images of skips


*Figure A.2.2: 6 m³ skip: cardboard, plastics, plants.*

*Figure A.2.3: 6 $m^3$ skip: Styrofoam, gypsum, tiles, sink, wooden pallet.*

*Figure A.2.4: 10 m³ skip: wood, Styrofoam.*

*Figure A.2.5: 6 m³ skip: double-glazed windows.*

*Figure A.2.6: 10 m³ skip: rooftiles, street tiles.*

*Figure A.2.7: 10 m³ skip: wood, doors, refrigerator.*

# Appendix B

## 1. Method

### 1.1 Construction year selection

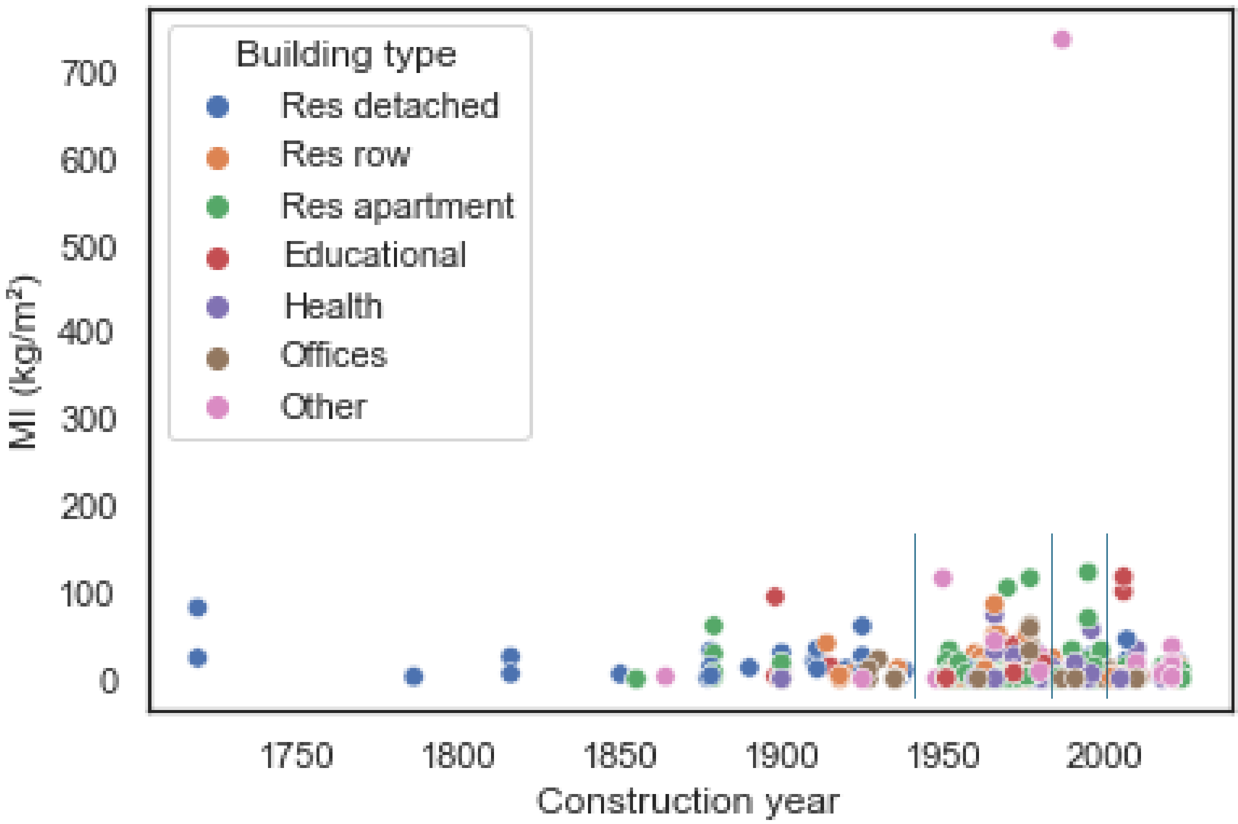


*Figure B.1.1: MI per construction year organized by building type. The lines indicate the break of construction year categorization.*

### 1.2 Material selection

*Table B.1.1: Number of projects (renovation and transformation) with that skip type and the mass percentage of the material compared to all the projects. The selected materials are marked in light grey.*

| Material type | Project count | Mass percentage (%) |
|---|---|---|
| Aggregates | 85 | 14.42 |
| Asbestos-containing material | 2 | 0.02 |
| Undifferentiated | 299 | 69.87 |
| Glass | 4 | 0.13 |

| | | |
|---|---|---|
| Gypsum | 24 | 5.15 |
| Hazardous waste | 4 | 0.00 |
| Insulation material | 6 | 0.38 |
| Metal | 11 | 0.72 |
| Other | 4 | 0.00 |
| Paper/cardboard | 77 | 1.24 |
| Roof-waste | 13 | 1.00 |
| Synthetic material | 25 | 0.59 |
| Wood | 88 | 6.48 |

*Table B.1.2: project count and mass percentage per material from renovation.*

| Material type | Project count | Mass percentage (%) |
|---|---|---|
| Asbestos-containing material | 2 | 0.03 |
| Undifferentiated | 278 | 76.86 |
| Roof-waste | 12 | 1.05 |
| Hazardous waste | 4 | 0.00 |
| Gypsum | 14 | 1.47 |
| Glass | 3 | 0.17 |
| Wood | 76 | 6,28 |
| Insulation material | 4 | 0.12 |
| Synthetic material | 20 | 0,57 |
| Metal | 6 | 0.37 |
| Other | 4 | 0.00 |
| Paper/cardboard | 66 | 0.97 |
| Aggregates | 73 | 13.37 |
| | | 100 |

*Table B.1.3: project count and mass percentage per material from transformation.*

| Material type | Project count | Mass percentage (%) |
|---|---|---|
| Asbestos-containing material | 0 | 0.00 |
| Undifferentiated | 21 | 54.86 |
| Roof-waste | 2 | 2.59 |

| | | |
|---|---|---|
| Hazardous waste | 0 | 0.00 |
| Gypsum | 10 | 13.04 |
| Glass | 1 | 0.03 |
| Wood | 12 | 7.53 |
| Insulation material | 2 | 0.92 |
| Synthetic material | 5 | 1.03 |
| Metal | 5 | 1.48 |
| Other | 0 | 0.00 |
| Paper/cardboard | 11 | 1.83 |
| Aggregates | 12 | 16.69 |
| | | 100 |

## 1.3 Undifferentiated and Aggregates content

*Table B.1.4: mass percentages of material content CDW skips.*

| | |
|---|---|
| Gravel (Puin) | 5,7% |
| Iron (IJzer) | 3,6% |
| Paper/cardboard (Papier/karton) | 0,4% |
| Sand (Zeefzand) | 25,0% |
| Fine gravel (Fijn puin) | 24,3% |
| Rough gravel (Grof puin) | 24,9% |
| Residue (Residu) | 8,9% |
| A wood (ASI-hout) | 1,1% |
| B wood (B-hout) | 6,3% |

*Table B.1.5: mass percentages of material content aggregates skips.*

| | |
|---|---|
| Limestone (Kalkzandsteen) | 30,0% |
| Brick (Baksteen) | 35,0% |
| Roof tiles (Dakpannen ) | 20,0% |
| Other (Overig puin ) | 15,0% |

## 2. Results

*Table B.2.1: number of renovation projects per material and building type.*

| Material type | Res detached | Res row | Res apartment | Educational | Health | Offices | Other |
|---|---|---|---|---|---|---|---|
| Aggregates | 8 | 14 | 23 | 4 | 8 | 8 | 8 |
| Asbestos-containing material | 0 | 1 | 0 | 0 | 1 | 0 | 0 |
| Undifferentiated | 32 | 78 | 62 | 11 | 27 | 34 | 34 |
| Glass | 0 | 1 | 1 | 0 | 0 | 0 | 1 |
| Gypsum | 1 | 0 | 10 | 0 | 1 | 1 | 1 |
| Hazardous waste | 0 | 1 | 2 | 0 | 1 | 0 | 0 |
| Insulation material | 0 | 0 | 2 | 0 | 1 | 1 | 0 |
| Metal | 1 | 0 | 4 | 0 | 1 | 0 | 0 |
| Other | 0 | 0 | 2 | 2 | 0 | 0 | 0 |
| Paper/cardboard | 1 | 23 | 31 | 2 | 4 | 5 | 0 |
| Roof waste | 1 | 3 | 4 | 1 | 0 | 1 | 1 |
| Synthetic material | 0 | 6 | 10 | 1 | 0 | 0 | 3 |
| Wood | 7 | 16 | 23 | 4 | 4 | 13 | 9 |

*Table B.2.2: number of transformation projects per material and building type.*

| | Educational | Offices | Other |
|---|---|---|---|
| Aggregates | 2 | 5 | 5 |
| Asbestos-containing material | 0 | 0 | 0 |
| Undifferentiated | 3 | 7 | 11 |
| Glass | 0 | 1 | 0 |
| Gypsum | 1 | 4 | 5 |
| Hazardous waste | 0 | 0 | 0 |
| Insulation material | 0 | 1 | 1 |
| Metal | 1 | 2 | 2 |
| Other | 0 | 0 | 0 |
| Paper/cardboard | 2 | 5 | 4 |

*Table B.2.3: number of renovation projects per material and construction year category.*

| Material | Before 1945 | 1945-1970 | 1970-2000 | 2000 and later | year unknown |
|---|---|---|---|---|---|
| Aggregates | 9 | 17 | 25 | 11 | 11 |
| Asbestos-containing material | 0 | 1 | 0 | 1 | 0 |
| Undifferentiated | 48 | 60 | 95 | 30 | 45 |
| Glass | 0 | 0 | 3 | 0 | 0 |
| Gypsum | 3 | 3 | 6 | 1 | 1 |
| Hazardous waste | 0 | 0 | 3 | 0 | 1 |
| Insulation material | 0 | 1 | 1 | 2 | 0 |
| Metal | 0 | 3 | 2 | 1 | 0 |
| Other | 1 | 2 | 1 | 0 | 0 |
| Paper/cardboard | 5 | 18 | 25 | 8 | 10 |
| Roof waste | 1 | 2 | 7 | 0 | 1 |
| Synthetic material | 1 | 8 | 9 | 1 | 1 |
| Wood | 12 | 17 | 24 | 9 | 14 |

*Table B.2.4: number of transformation projects per material and construction year category.*

| Material | Before 1945 | 1945-1970 | 1970-2000 | 2000 and later |
|---|---|---|---|---|
| Aggregates | 4 | 3 | 4 | 1 |
| Asbestos-containing material | 0 | 0 | 0 | 0 |
| Undifferentiated | 6 | 5 | 8 | 2 |
| Glass | 1 | 0 | 0 | 0 |
| Gypsum | 3 | 2 | 4 | 1 |
| Hazardous waste | 0 | 0 | 0 | 0 |
| Insulation material | 1 | 0 | 1 | 0 |
| Metal | 2 | 1 | 2 | 0 |
| Other | 0 | 0 | 0 | 0 |
| Paper/cardboard | 3 | 4 | 3 | 1 |
| Roof waste | 0 | 2 | 0 | 0 |
| Synthetic material | 2 | 1 | 1 | 1 |
| Wood | 3 | 5 | 3 | 1 |