Dynamic MFA Modelling on Individual Building Level

Exploring Secondary Material Supply in the City of Hamburg

M.Sc. Industrial Ecology

Kim Hannah Gülck

Universiteit Leiden
The Netherlands

TU Delft

Dynamic MFA Modelling on Individual Building Level

Exploring Secondary Material Supply in the City of Hamburg

by

Kim Hannah Gülck

to obtain the degree of Master of Science in

Industrial Ecology

at Delft University of Technology and Leiden University.

Student number:	s3289133	Leiden University
	5666511	TU Delft
Thesis committee:	Dr. Tomer Fishman	Leiden University, first supervisor
	Dr. Benjamin Sprecher	TU Delft, second supervisor

24th of November, 2023

Cover Image: Author unknown.
Source:
https://upload.wikimedia.org/wikipedia/commons/3/31/Hamburg_Jungfernstieg_%281890-1900%29.jpg

Acknowledgements

The past two years have been the most challenging yet simultaneously the most rewarding time of my life. I extend my gratitude to all the individuals in the Industrial Ecology programme who contributed to creating a welcoming, inspiring, motivating, and enjoyable atmosphere. Thanks to those who challenged my opinions, broadened my horizons and encouraged me to think outside the box. With this master's programme including a fair amount of group work, I especially want to thank everyone who made an effort to make the collaborative experience fun and successful. Overall, I would like to emphasise, that I never experienced such a respectful educational environment, where opinions are valued, and teachers are genuinely committed to imparting knowledge to their students. This experience is something I will carry with me wherever I go. At this point, I would also like to send a heartfelt thank you to Thomas Kölzer, without whom I might never have found my way to the Netherlands.

I want to express my gratitude to Tomer Fishman, who has been a very present and engaged first supervisor throughout this project. He not only challenged me with his questions but also ensured I'm not being too humble about my work. I also thank Benjamin Sprecher for agreeing to be my second supervisor despite his busy schedule. Other individuals I thank for their help during this thesis journey include Catrin Böcher for our insightful exchanges of thoughts, Karel Jenis for taking the time to explain his approach in detail, enabling me to apply it myself, and Maarten van 't Zelfde for his ArcGIS support. I am also grateful to Shoshanna Sax and Maud Lanau for taking the time to briefly discuss some of my ideas along the way.

I would also like to express my gratitude to all my friends, near and far, who kept checking in on me in the past months, sending good wishes and motivating words. Your support, no matter the distance, is deeply appreciated.

To my dear friends in Delft – you know who you are – thank you for the continual flow of uplifting words, open ears, and long hugs. I never imagined having such a fun, warm-hearted and supportive group of friends. You have made this place my home away from home.

Finally, I would like to emphasize the immense gratitude I feel towards my family. To my 'mum-in-law' for providing me with home-cooked meals, allowing me to focus on my deadlines. To my grandmother and my late grandfather, who early on ensured I would have a financial buffer if I ever chose to study abroad. I am truly grateful to my parents for their unwavering belief in me, supporting me every second of my life, and providing me with the confidence and ease that carries me through life. Last but not least, from the bottom of my heart, I want to thank Noel – without you, I wouldn't be where I am today.

Kim Hannah Gülck
Delft, November 2024

Summary

This research delves into the challenging task of exploring secondary materials supply from existing building stocks, crucial for sustainable resource management in the face of climate change. Focused on Hamburg, Germany, the study employs a unique combination of GIS-based bottom-up building stock analysis and dynamic Material Flow Analysis (dMFA) at the individual building level. Unlike previous studies, this approach specifically explores the dynamics of single buildings based on their unique characteristics, such as function and building age.

The research explores the question of to what extent Hamburg's construction sector can meet its material demand for stock maintenance through secondary materials until 2075. The study emphasizes the often-overlooked impact of regional and local dynamics, making Hamburg an ideal case study. The city's lack of policies regarding primary material consumption in construction adds relevance to the investigation.

By addressing five sub-research questions, the study comprehensively examines current material stocks, future outflows caused by demolition and renovation, future inflows for maintenance of the building stock and replacement construction, and the secondary material potential of outflows. The methodology involves quantifying material masses through GIS analysis and the application of material intensities for different building types and age cohorts. The obtained results feed into the dynamic MFA model.

Recommendations arising from the findings include preparing for efficient brick recycling, developing storage concepts for secondary materials based on the determined spatio-temporal characteristics of outflows and initiating policy discussions on reducing primary material consumption in construction. This research not only contributes to the field of Industrial Ecology by extending the methodology for material stock and flow research on the local level but also has practical implications. Stakeholders in Hamburg, including policymakers, urban planners, and waste operators, can leverage the developed methodologies and results for informed decision-making. The study provides a blueprint for future research in other urban regions, showcasing the potential of openly available cadastre data and emphasizing the importance of addressing the complexities of material flows at a granular level.

Contents

List of Figures

List of Tables

Nomenclature

Abbreviations

Abbreviation	Definition
CDW	Construction and Demolition Waste
dMFA	Dynamic Material Flow Analysis
EOL	End-of-Life
GIS	Geographic Information System
GFA	Gross Floor Area
HH	Hansestadt Hamburg (*Hanseatic City of Hamburg*, official name of the City of Hamburg)
IE	Industrial Ecology
MFA	Material Flow Analysis
MFH	Multi-Family Home
MI	Material Intensity
SFH	Single-Family Home
UFA	Useful Floor Area
UM	Urban Mining

1

Introduction

The supply of materials is fundamental for the functioning of all sectors in our economy and therefore of large interest to society. At the same time, the extraction of raw materials is the cause of large environmental impacts, changing ecosystems and causing biodiversity loss (Gallego-Schmid et al., 2020; Schebek et al., 2017). The most impactful sector in terms of material consumption is the building and construction sector, annually consuming about 50% of global materials (Gallego-Schmid et al., 2020). This material consumption naturally causes a considerable amount of GHG emissions, namely around a quarter of annual global emissions (Heinrich & Lang, 2019). In Germany, 53% of all waste is caused by the construction industry, of which 37% are mineral materials. Approximately 5-10% of EU total energy consumption is related to construction material production (Bründlinger et al., 2021).

As about 90% of all material stored in long-lasting goods in anthropogenic stocks is believed to be found in buildings and infrastructure (Schiller et al., 2019), researchers have been attempting to quantify this stock and its characteristics. The driving motivation behind this research is the idea, that assets in this anthropogenic stock, such as buildings or infrastructure, can serve as so-called 'urban mines', supplying secondary materials, and simultaneously reducing waste streams. The process of sourcing these materials is usually referred to as urban mining (UM) (Schiller et al., 2015). In order to exploit a mine, its composition and characteristics need to be known. Quantities and qualities of the stocked materials require exploration to build a basis for the estimation of secondary materials suitable for recycling, ultimately reducing primary material consumption, the extraction of virgin resources and the resulting environmental impacts (Miatto et al., 2019; Ortlepp et al., 2016; Schiller et al., 2018).

1.1. Problem Introduction

While anthropogenic stocks are expected to be highly important in providing resources in the near future (D. Müller, 2006), extracting secondary materials from the building stock remains a difficult challenge, as the stock is not designed to serve as a source for recyclable or reusable material (Gülck, 2022). Knowledge about the distribution and quantities can therefore be regarded as the first step towards making these potential secondary material sources more accessible (Miatto et al., 2019; D. Müller, 2006).

Studying stocks can entail a twofold approach. On the one hand, the quantities and types of materials in the stock have to be determined. On the other hand, the behaviour or better-called the *dynamics* of the stock over time have to be modelled. Adding the temporal scope accounts for the fact that buildings have significantly longer lifespans than other manufactured goods, which also means that the materials they are composed of are often in use for decades and the point in time where materials become available is not easily determinable. Besides building lifetime characteristics, maintenance requirements influence material in- and outflows and must therefore be systematically explored (Wiedenhofer et al., 2015). Göswein et al. (2019) state that studying and understanding such dynamics *'is needed to govern building stocks toward a more environmentally sustainable state'* (p. 9993).

Multiple studies have already been conducted on the material stocks and flows in the built environment in Germany. Most studies use the method of material stock accounting or static material flow analysis (Haberl et al., 2021; Ortlepp et al., 2018; Ortlepp et al., 2017; Schiller et al., 2017), where static refers to the approach of quantifying stocks and flows in one specific point in time. Few studies use dynamic Material Flow Analysis (Heinrich & Lang, 2019; Pauliuk & Heeren, 2021; Volk et al., 2019), an approach to predict stocks or flows over a longer time frame. The time scope for the static analyses is mostly set to 2010 or 2018, while the dynamic analyses explore time intervals until 2030 or 2050. While the studied stocks mainly include residential and non-residential buildings, Umweltbundesamt (2022b) also considers infrastructure, such as roads, railways or multiple types of underground engineering infrastructure.

Other studies suggest that the exploration of this question is not only relevant on a national level but could also be substantial on a regional or local level, as construction materials often come in bulk, limiting feasible transport distances to about 50 km (Schiller et al., 2020; Schiller et al., 2018). A regional context also facilitates accounting for local specifics, like city-level climate policies for construction or material-related local particularities and allows for a better relation of knowledge to practice (Heinrich & Lang, 2019; Ortlepp et al., 2016; Schiller et al., 2019; Schiller et al., 2018). Local knowledge about outflowing materials might also incentivise the better organisation of End-of-Life (EOL) operations as well as the establishment of market and logistic mechanisms for recovery, which are currently a main barrier to the supply and use of secondary materials (Adams et al., 2017). Furthermore, it is believed to uncover the need for investment in innovative recycling technologies (Ortlepp et al., 2016; Schebek et al., 2017).

Considering the described relevance of studying stock and flows locally, this research is conducted within the geographical scope of the city of Hamburg, located in the north of Germany. Its population of almost 1.9 million citizens - making it the second largest city in the country - is expected to continue growing slightly but almost approach stagnation towards the middle of the century (Demografie Portal, 2023). The city has a long history of major urban development interventions. Being heavily destroyed in World War II, a large share of residential buildings stem from the post-war period of 1949-1978. In the recent two decades, large redevelopment of former port and industrial areas is taking place. While the new city quarter on the northern shore of the river Elbe is almost complete, the construction of another city quarter is starting on the southern shore. With these major city development plans underway, the city continues to largely add materials to its building stock. In the face of required climate action, Hamburg has issued a so-called 'Klimaplan', which sets the target of reaching a climate-neutral building stock in 2045 (Stadt Hamburg, 2022). This relates to the energy consumption during the use stage of buildings but completely neglects the impact of construction materials. Without any targets to reduce primary construction material consumption, Hamburg makes an interesting case for obtaining insights on the current material stocks and future flows and ultimately 'putting materials on the map' for policymakers and politicians in the city.

1.2. Research Objective

This research aims to quantify the detailed spatial distribution of materials in Hamburg, Germany. Subsequently, using building-level data, the future material inflows and outflows from buildings caused by the maintenance of the stock over time are estimated. Furthermore, the potential future supply of secondary materials will be derived from the outflows and compared with the future demand for materials required for stock maintenance. These findings can predict the magnitude of potential supply and demand mismatches, analysing the dependency on primary materials.

The main question that will be addressed in the proposed research is as follows:

To what extent can the construction sector's material demand for stock maintenance in Hamburg (Germany) be satisfied by secondary materials sourced from the existing building stock until 2075 and which implications can be drawn from the determined level of self-sufficiency?

1.3. Relevance of the Research

Firstly, the topic of research is adding to the field of Industrial Ecology (IE) by contributing to the existing research on material stocks and flows, especially extending it to the local-level research on material flows and stocks in the specific region of Hamburg. By first performing a GIS-based bottom-up stock analysis and then applying prospective dynamic Material Flow Analysis (dMFA), based on the stock analysis results, two methods widely used in the field of IE are utilised in a rare combination. The approach is especially unique in acquiring and using spatially explicit data on the level of individual buildings, retaining this resolution also during the performance of the prospective dMFA. Thus, the research follows what can be called a 'true' bottom-up approach, aiming to represent individual buildings' properties as detailed as possible and thereby adding to the methodologies of IE. Regarding GIS results, the study will use cadastre data, which has not been used in other studies so far, producing a new data point for comparison with prior research. As no MFA studies have been conducted in the context of Hamburg so far, these results will be novel.

Secondly, the topic is relevant in a societal context. After obtaining a detailed insight into the building stock characteristics and dynamics of Hamburg, the results should serve as a basis to inform policymakers in Hamburg about current and future material quantities in stocks and flows in the city and trigger a discussion on Hamburg's (currently lacking) goals regarding the reduction of primary material consumption in construction. Ideally, this will lead to further detailed research on the topic, eventually motivating the implementation of a policy setting clear goals for the reduction of future primary material consumption.

1.4. Sub-Research Questions

(1) What are the current stocks of materials in buildings in Hamburg?

(2) What will be the future material outflows from Hamburg's building stock, caused by demolition and renovation activities?

(3) What will be the future material inflows to maintain Hamburg's building stock?

(4) How high is the share of outflows that can be recycled to serve as secondary material for the maintenance of Hamburg's building stock?

(5) Which implications arise from the determined characteristics and dynamics of the building stock and how are they relevant to different actors in Hamburg?

1.5. Research Outline

The outline of this research is visualised in a research flow diagram in Figure 1.1.

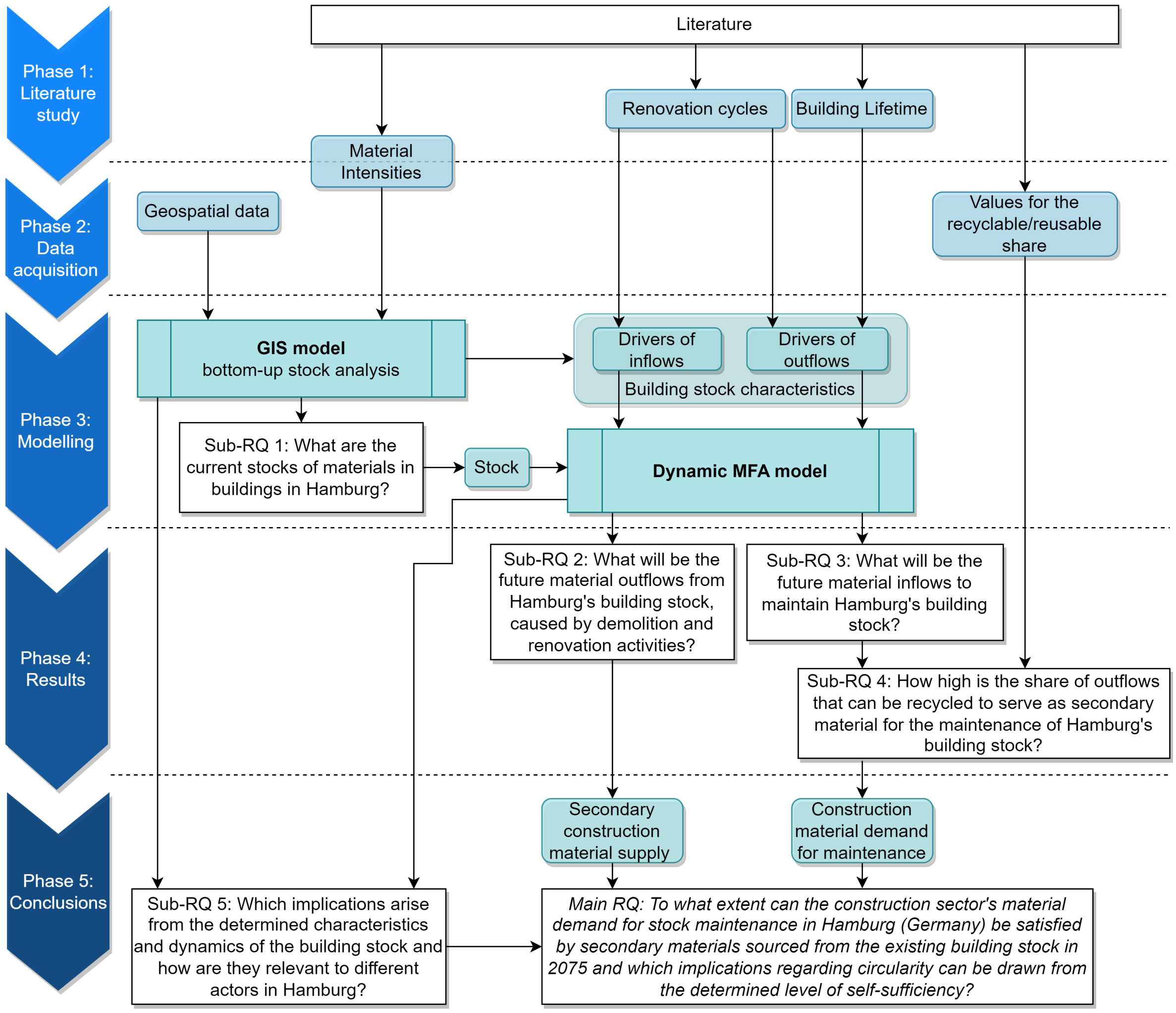

Figure 1.1: Research Flow Diagram.

2
Background

2.1. Geographic Information System

Geographic Information System (GIS) is a technology and methodology used to collect, process, organise, analyse and visualise spatial data. Spatial data connects an object's specific location on the earth's surface, the *where*, with its characteristics, the *what* (Esri, 2023b). Due to these properties, it is widely applied in e.g. environmental science, urban planning or disaster management, aiding informed decision-making regarding spatial problems. Examples of such include the utilisation of GIS for analysing and mapping flood vulnerability in Vietnam (Hien et al., 2005) or for identifying and characterising populations living close to high-voltage transmission lines to evaluate potential health risks (Wartenberg et al., 1993). The interested reader can find various other examples of GIS applications in relation to climate impacts online (Esri, 2023a).

Spatial studies often follow a framework called *The Geographic Approach*, a five-step process that structures the different phases required for moving from spatial problems to potential solutions by studying and analysing spatial datasets in a detailed and comprehensive way (Baumann, 2009). The five steps are displayed and explained in Figure 2.1. Although presented in a linear organisation, the framework is to be understood as an iterative process, where it is often necessary to review a preceding step to reach the analysis' goal. This is especially true between steps 2,3 and 4. The framework is applied for the first part of this research, the GIS bottom-up building stock analysis. The steps also serve as the structural backbone of Section 3.2 in an effort to communicate the analysis' work in a transparent and reproducible way.

2.2. Material Intensities

Material intensities (MIs) are coefficients describing the amount of material present in a defined spatial unit. In relation to buildings they usually specify the amount of a particular material (in kg or tons) per m^3 (gross volume) or m^2 (gross floor area), depending on the building characteristics (e.g.

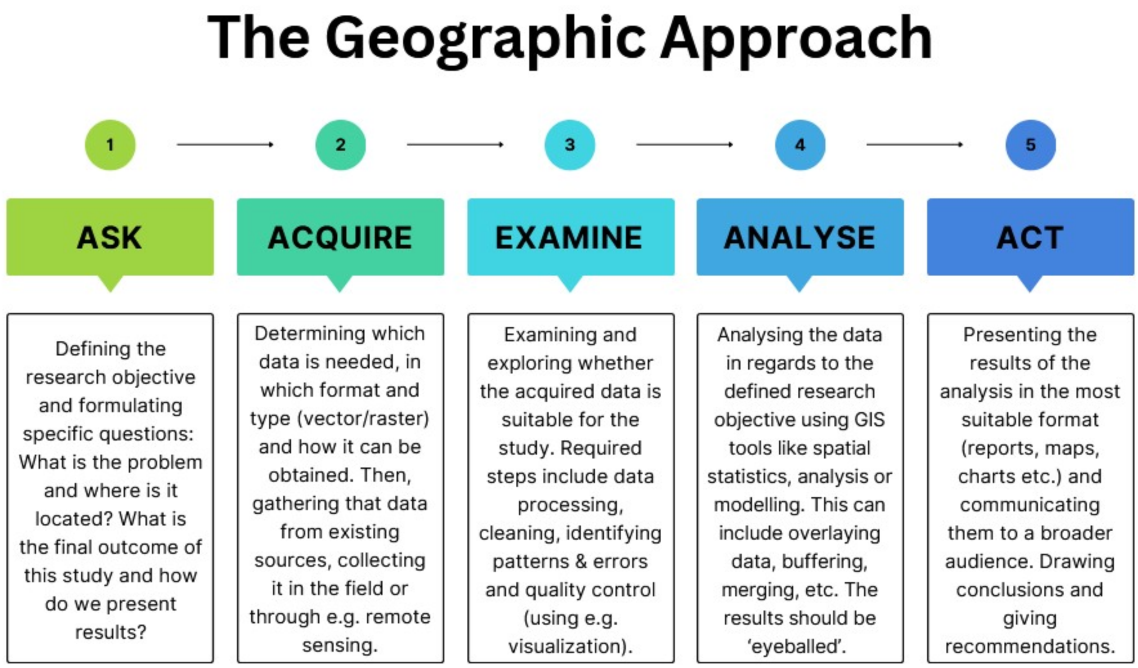

Figure 2.1: The Geographic Approach. Author's visualisation based on (Baumann, 2009)

function) and sometimes its age. By multiplying the MI with the corresponding spatial unit the absolute stock of materials is determined for a defined spatial scope (Ortlepp et al., 2016; Tanikawa et al., 2015). Examples of MI-use in building stock studies can be found in Section 2.5.

2.3. Material Flow Analysis

Material Flow Analysis (MFA) is a tool commonly used in Industrial Ecology research. Based on mass balance principles, it is applied to study stocks and flows, as well as their service provision, at different spatial and temporal scales in our society's metabolism (Kaufman, 2012). Static MFA is applied to investigate flows and stocks of materials at one point in time, e.g. in a specific year. Dynamic MFA is used to prospect future stocks or flows based on either a known stock (*stock-driven approach*) or based on known flows, often inflows (*flow-driven approach*). Results of MFA research can be linked to emission values, for example, to compare different building types not only in terms of their material consumption but also in terms of their impact on emissions.

2.4. Bottom-Up vs. Top-Down Approach

Accounting for the materials in anthropogenic stocks can be done by either employing a bottom-up or a top-down approach. This section briefly explains these two approaches specifically in relation to material stock accounting before elaborating on their relevance in the context of MFA studies.

The bottom-up approach is characterised by its detailed and granular assessment of material stocks. Stocks are analysed and quantified by examining individual objects in a defined area (e.g.

using GIS) and at a certain time. The latter is the reason why it is also often called a static approach (Augiseau & Barles, 2017; Tanikawa et al., 2015). The material quantities of individual objects are then aggregated, determining the total stock. To calculate these material quantities, material intensities, often also called material intensity coefficients, are used. MIs describe how much of a particular material is present within a defined unit of measurement, e.g. a specific area or one studied object, depending on the characteristics of the object (e.g. age or type) (Haberl et al., 2021; Tanikawa et al., 2015). Bottom-up studies, therefore, lead to results specifically valuable in a regional context, that can e.g. help policymakers make informed decisions about circular economy strategies or inform the waste management industry about the future composition and distribution of material flows.

Top-down approaches rely on macroeconomic data and statistics on material flows, which are aggregated over time. Stocks can only be estimated by determining the initial stock in a certain year and summing the net addition to stock over the study's time scope, thus lacking spatial differentiation of stocks (Haberl et al., 2021; Schiller et al., 2017; Tanikawa et al., 2015). This approach is mainly used for analyses on a national level, as statistics on construction activity, material consumption and other relevant data such as population are mostly recorded in the format of national statistics (Han et al., 2018).

Next to stock accounting, the different approaches are also relevant to studying the flows of materials. As Tanikawa et al. (2015) point out, flows are inherent in top-down models due to the nature of the input data, already building the bridge to MFA studies. They state that this has led to confusing naming conventions of methods and thus introduce the term *demand-driven modelling* next to top-down accounting. Demand-driven modelling is a dynamic modelling approach based on the demand for e.g. floor space in buildings over time, influenced by factors such as population or economic indicators (Tanikawa et al., 2015). While the material content of the objects in demand is determined by using material intensities (bottom-up), the temporal aspect, such as the lifetime of buildings or population development, is modelled based on statistical or macroeconomic data (top-down) (Tanikawa et al., 2015).

Top-down approaches are strong in determining material stocks and flows on larger scales, allowing e.g. for comparison of material consumption or stocks between countries or even larger entities. As mentioned before, data used in top-down research relates to material flows. Stocks have to be derived from the net addition to stock. While this method is strong in determining inflows, outflows are generally more difficult to determine, as waste statistics are not complete or detailed enough regarding material composition (Schiller et al., 2017).

Bottom-up approaches are strong in capturing stocks of diverse materials in small-scale scopes and the method is believed to be more flexible and adaptable to the specific stock or flows that are to be determined (Schiller et al., 2017). In contrast to the top-down, the bottom-up approach allows for spatial differentiation of stocks, due to its applicability on small scales. However, building a detailed inventory for bottom-up analyses is a time-consuming and difficult undertaking and entails the risk of ending with incomplete inventory results (Schiller et al., 2017).

In the German context, Schiller et al. (2017) and Schiller et al. (2015) made an effort to combine both approaches on a national scale, hoping to gain a more complete insight into stocks and flows of buildings, infrastructure and durable goods in the year 2010. For the top-down part, they use macroeconomic data on domestic extraction, material imports and exports and domestic disposal. For the bottom-up part, they acquire data on useful floor area (UFA) from statistics and apply MIs. For stock accounting, the bottom-up approach yields smaller results than the top-down approach. The difference is especially large for wood and other materials, but also for minerals. For the latter, the stock through bottom-up accounting was determined at approximately half the size of the top-down accounting. Regarding the flows, they find that the results for inflows are higher with the top-down approach and results for outflows are larger using bottom-up. Top-down approaches tend to underestimate outflows due to construction wastes by-passing waste treatment facilities and therefore not being recorded in official statistics (Schiller et al., 2017). Further examples of the application of the aforementioned approaches in prior research can be found in the next section.

2.5. Prior Research

This section gives a short introduction to relevant prior research in the context of this study. Next to different approaches to stock accounting, studies employing MFA are presented. Lastly, the combination of GIS-based stock accounting and MFA in literature is explored.

Stock Accounting

Various studies accounting for stocks employ the basic principle of determining the number of buildings, their floor space or similar data, followed by the multiplication of these units with corresponding MIs. This bottom-up approach to stock accounting is often complemented by the use of GIS.

Tanikawa and Hashimoto (2009) determine the material stock of buildings, roadways and railways in Wakayama, Japan and Salford Quays, Manchester, UK, at multiple snapshots in time between 1849 and 2004, introducing the method of 4d-GIS. Their approach combines spatial and temporal dimensions, utilising GIS for spatial distribution and introducing a temporal scope through the fourth dimension. Furthermore, their research investigates the demolition curve of buildings, utilising the knowledge about the change in stock over time. The stock of buildings is determined from a mix of GIS data, paper maps, aerial photos and other pictures. The stock of materials in individual buildings is calculated by multiplying the building's total floor area by MIs.

In a broader context, Tanikawa et al. (2015) extend the application of GIS-based bottom-up accounting to evaluate the material stock of buildings and infrastructure across Japan from 1945 to 2010. This retrospective analysis portrays the evolving stock dynamics over the specified period.

Shifting the focus to European cities, both Kleemann et al. (2017) and Lanau and Liu (2020) adopt GIS-based bottom-up approaches to establish a foundation for future urban resource cadastres in Vienna, Austria, and Odense, Denmark, respectively. The former categorises buildings into three building types (residential, commercial and industrial) of five age cohorts, measured by gross volume, applying respective MIs generated within the research. Lanau and Liu (2020) determine the stock of materials in residential and non-residential buildings as well as in road and pipe networks in 2018. They calculate the stock of nine different materials for individual buildings with respect to the building's function and age and per floor area, also differentiating between above and below-ground stocks. The strength of the approach employed by both studies is the detailed information on the location of materials in the stock in comparison to top-down approaches based on statistical data. Kleemann et al. (2017) claim that this knowledge is equally important to the knowledge of the overall stock, as it allows for predicting the occurrence and location of construction and demolition waste (CDW) occurrence in a detailed manner, serving as the basis for the prediction of secondary material availability (Kleemann et al., 2017).

Haberl et al. (2021) introduce a distinctive methodology, utilising earth observation data and open street map data to calculate the stock of eight different materials in buildings and infrastructure in Austria and Germany. From this data, they derive built-up surface area, building height and building type, subsequently applying MIs for five different building types (single-family homes, multi-family homes, industrial/commercial, lightweight and high-rise). The age of buildings is not considered. They determine the stock of materials at a spatial resolution of 10 meters, enhancing the ability to map material stock over larger areas while retaining a high level of detail. Haberl et al. (2021) state that this closes a gap between coarse estimates of material stock derived from night-time light data for extensive regions and granular stock accounting based on cadastre data only applicable in small areas.

Within a German context, the use of GIS or remote sensing data is rare. Schebek et al. (2017) employ GIS for stock accounting in non-residential buildings in the Rhine-Main area. The study applies MIs considering the function, age, and gross volume of individual buildings. As non-residential buildings are understood to be generally understudied in the German context (Ortlepp et al., 2016; Ortlepp et al., 2015; Schebek et al., 2017), this research gives interesting insights into the characteristics of the non-residential stock in the study's area. Factory and commercial/retail buildings are found to be the largest in number and one-third of the total building stock originates from before 1948, indicating the need for future renovation could be high (Schebek et al., 2017).

Ortlepp et al. (2015) and Ortlepp et al. (2016) also account for the stock of materials in German non-residential buildings, differentiating between seven different types and ten material groups. Financial data and statistics on building activity serve as a proxy for determining floor space in the absence of relevant data in German statistics. Similarly, Schiller et al. (2015) and Schiller et al. (2017) utilise statistical data on the floor area of residential buildings in Germany, multiplied by MIs to determine the stock of materials in Germany´s residential building stock. Although technically employing bottom-up approaches, the statistical nature of the data sources introduces a lack of spatial differentiation to the analyses.

MFA for Construction Materials

While stock accounting gives a full picture of the materials currently in buildings, MFA goes further by examining how construction materials move through their life cycle. D. Müller (2006) presents a first generic demand-driven dynamic MFA model and applies it to explore the flows of concrete connected to Dutch residential buildings between 1900 and 2100. In a top-down manner, the UFA in use depends on population development and average UFA per person, while outflows depend on the lifetime of buildings. Inflows to the material stock are calculated by applying MIs, following a bottom-up approach. Population and lifestyle are the driving forces of material cycles (D. Müller, 2006). Bergsdal et al. (2007) employ an adaptation of this model to determine the waste generation of concrete and wood from construction and demolition activity in a Norwegian context. The study considers the stock of UFA in residential buildings in the time frame 1900-2100. Furthermore, scenarios for population development, floor area per dwelling, person per dwelling and different lifetimes of buildings are developed.

Wiedenhofer et al. (2015) follow a demand-driven approach, modelling stocks and flows of non-metallic minerals in residential buildings, railways and roads in the EU25 for snapshots between 2004 and 2009. They consider a detailed categorisation of 72 residential building types and apply empirical growth, demolition and maintenance rates. The stock is calculated by multiplying the number of buildings by the respective volumetric MIs. Considering material demand for expansion and maintenance of the current stock, they find that a large share of material inflows is utilised to maintain the existing stock (Wiedenhofer et al., 2015).

Within a German context, Ortlepp et al. (2018) perform a static stock-driven MFA on multi-family homes (MFH). From statistical data on the total floor space in stock in 2010, they derive the stock of ten materials by applying MIs of five different age cohorts. Outflows and inflows are also derived from statistical data on construction and demolition in the year 2010. Schiller et al. (2018) introduce what they call a 'regionalized continuous MFA' to *'achieve a closed loop MFA of bulk materials in the construction industry along continuous material flows'* (p. 128). After estimating stock dynamics of residential and non-residential buildings based on population development and lifestyle characteristics, flows of concrete and brick are derived by applying MIs. Lastly, the study derives recyclable shares of materials from the outflows and compares their supply with the demand by region, taking into account limitations to the share of recycled content in construction materials. They find a surplus of recycled masonry aggregate in all regions (Schiller et al., 2018).

Combination of GIS-based Stock Accounting and MFA

Next to the studies focusing on either stock accounting or MFA, there is a small body of literature employing a combination of GIS-based stock accounting and MFA, which is a relevant approach to reaching the objective of this research.

For the city of Shanghai, China, Han et al. (2018) perform a bottom-up stock accounting analysis for residential buildings, roads and railways using GIS data as well as digitised historical maps. They calculate the current stock of materials utilising MIs per m^2 of floor area, rasterising the results in a 500m x 500m grid. Subsequently, the researchers determine material flows for the period between 1980 and 2010, employing a logistic function for the demolition curve of residential buildings. This research gives insights into Shanghai's patterns of material stocks and lows over space and time and generates implications for policies on sustainable urban infrastructure development and urban sustainability (Han et al., 2018).

Shifting the focus to European cities, Miatto et al. (2019) build a retrospective stock model based on historic maps, determining the material stock per building by applying element-based volumetric MIs. The utilised MIs are generated within the study. Due to the detailed knowledge of the retrospective stock, the study derives the average lifespan of buildings from real-world data. Applying this knowledge to the current stock Miatto et al. (2019) estimate the waste potential per material regarding the different building types and cohorts in the current stock. The study emphasises its contribution to the empirical estimation of building lifetime parameters, which are strong in generating context-specific material dynamics.

Using widely available Dutch GIS data, Verhagen et al. (2021) account for the material stock of individual buildings in Leiden, The Netherlands, by multiplying the building's floor space by an MI depending on the age and type. They consider four residential building types and three non-residential building types. Thereafter, they calculate material flows utilising data on planned demolition and construction projects between 2019 and 2030, provided by the municipality in the format of m^2 floor area to be demolished or constructed annually. The study does not consider renovation activities. The main goal of the study is to compare the recyclable fraction of the determined outflows from demolition with the calculated yearly demand. By this, the researchers aim to explore whether the Dutch goal of reducing primary material by 50% in 2030 can be reached, which they find not to be true for the city of Leiden.

Heeren and Hellweg (2019) propose a *'component-based, prospective, and probabilistic modelling approach to quantify the material composition of Swiss residential buildings, which can then be aggregated geographically to model building material stocks and flows of regions.'* (p. 254). The study determines building volumes from 3D GIS data sets for residential buildings in Switzerland, calculating material stocks in a bottom-up style by applying volumetric MIs. Although results can be aggregated to regional scopes, the study generally presents results on a national level. Furthermore, the paper does not go into detail on the stock accounting results but rather focuses on utilising the results as input for the MFA model. The latter includes probabilistic scenarios for the dynamics of the building stock and prospects material flows in a dynamic manner, also connecting emissions to the final results. The study uses a unique approach, modelling individual building lifetimes rather than applying constant demolition rates to the total stock (Heeren & Hellweg, 2019).

In a German context, Heinrich (2019) utilises GIS data to determine the building stock of single-family homes (SHF) and MFH in Freiham, a district of Munich, Germany. The researcher calculates the stock of materials by multiplying the gross volume per year by the respective MIs per building type. Using the generated knowledge on the building stock, he builds a dynamic MFA model considering demolition, new construction, replacement construction and renovation of buildings. Lastly, the study considers recyclable fractions, ultimately determining the future level of self-sufficiency of recycled aggregates and metals in the district.

Lastly, some general findings of a critical review by Göswein et al. (2019) regarding dynamic assessments of construction materials in the urban context should be mentioned. Overall MFA and GIS are regarded as useful tools to model spatial dynamics of urban building stocks, with GIS contributing to the spatial component and MFA to the temporal one (Göswein et al., 2019). This combination is also regarded as useful in serving urban mining strategies. Furthermore, the study finds that renovation is mostly studied utilising top-down approaches and is overall less investigated than construction and demolition. Finally, Göswein et al. (2019) emphasise the strength of GIS in communicating the results of spatial studies to policymakers.

2.6. Recycling of Construction Materials

Within this study, recycling is understood as a process where a potential waste material is processed and turned into a new product. In contrast, reuse relates to the repeated use of an object in its original state and purpose. Reuse requires buildings to be designed for disassembly, so structural components can be recovered while maintaining their qualities (Gallego-Schmid et al., 2020). In practice, disassembly is today often hindered by non-reversible joints and unclear compliance with building standards (Kühlen, 2016), hindering the reuse of building parts. Recycling, however, is already put into practice, mainly focusing on the production of recycled aggregates (Di Maria et al., 2018). According to statistics, Germany has high aggregate recycling rates, that also comply with European regulations on CDW recycling. Still, almost all aggregates are used in low-quality applications (Di Maria et al., 2018). This phenomenon is called 'downcycling' and occurs for example in the recycling of concrete, where recycled aggregates are used as road fillers on a large scale (Di Maria et al., 2018). The best recycling scenario for concrete is its use as recycling aggregate in new concrete. This application would also prevent excess quantities of low-quality recycled aggregates that occur in countries such as The Netherlands (Di Maria et al., 2018). However, high-quality recycling of concrete currently faces barriers, such as reaching the same quality standards as aggregates from virgin materials, to avoid serious quality issues in the concrete mixture (Di Maria et al., 2018). Although this short example focuses on concrete, it illustrates the multi-fold challenges to construction material recycling and the general complexity of the topic.

3

Methods and Data

This research applies two main methods. It quantifies material masses in Hamburg's current building stock using a GIS bottom-up building stock analysis. Subsequently, this data serves as one of the inputs to the dynamic MFA model, which has the objective of estimating future material in- and outflows caused by maintaining the building stock. Furthermore, the study requires data on the material intensity (MI) of different building types as input to both, the stock analysis and the MFA model, which is discussed in Section 3.1. The acquisition of spatial and attribute data as well as its processing and analysis in the context of the GIS bottom-up building stock analysis are explained in Section 3.2. The input data and modelling choices of the dynamic MFA model are explained in detail in Section 3.3.

3.1. Material Intensity Data

This research applies material intensities (MIs) available on a publicly accessible online database (IÖR, 2023), which is provided by the *Leibniz-Institut für ökologische Raumentwicklung*, a German research institute located in Dresden. The MIs are representative in the German context and are developed through a series of research done by members of the research institute (Gruhler & Böhm, 2011; Gruhler & Deilmann, 2015, 2017). They are based on synthetic building types, which represent prevailing construction methods, building elements and materials for a certain type of building and a certain age in a national German context. I choose this set of MIs as they are the most extensive collection of MI values in a German context, covering a well distinguished range of different building functions. Additionally, the open access database makes the values accessible for everyone's use, allowing future researchers to apply the same MIs to their studies and also ensuring reproducibility of this analysis. Furthermore, prior research such as Haberl et al. (2021) or Heinrich (2019) already partly utilises these MIs, which makes results more comparable.

The database defines different MIs for subcategories and age cohorts of residential and non-residential buildings as visualised in Figure 3.1. Single-family houses (SFH) encompass buildings with one or two housing units, multi-family houses (MFH) include all residential building with more than two units. For SFH, the source only distinguishes between four age cohorts, the oldest being 'before 1949'. For reasons of consistency, I align the age cohorts of SFH with the five available cohorts for MFH, meaning the cohorts 'before 1919' and '1919-1948' have the same values for SFH. For garages, I calculate an MI based on expert assumptions and the MI for garages used by Haberl et al. (2021). A detailed explanation of this calculation is presented in the supplementary information (SI).

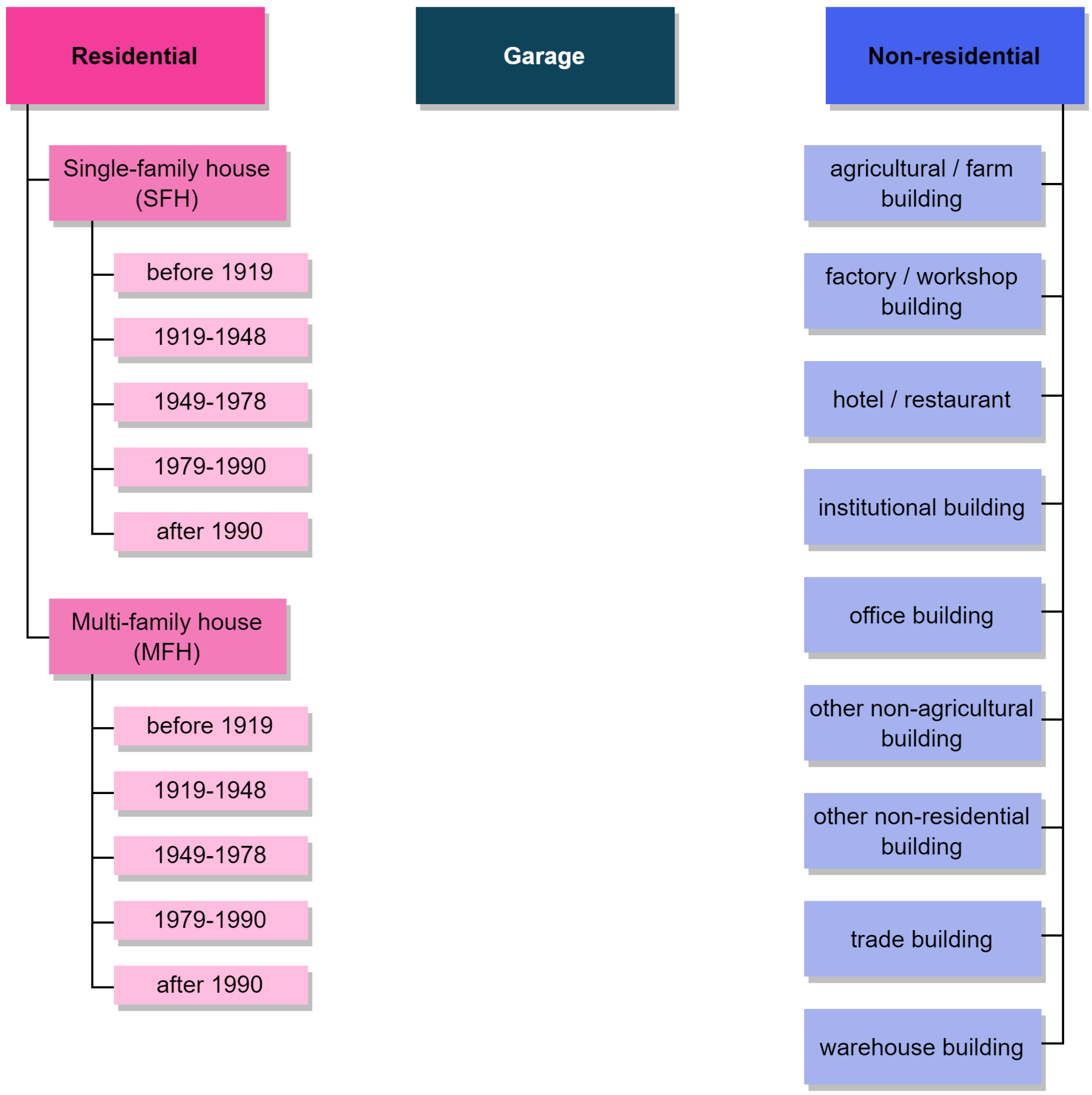

Figure 3.1: Building classification for material intensities. Author's visualisation.

The selected MIs from the IÖR database cover the following materials: Concrete, brick, asbestos, other minerals, lumber & processed wood, other renewable materials, plastics, bituminous, FE-metals, non FE-metals. This research excludes asbestos, as its use is banned in Germany since 1993 due to being highly carcinogenic and the cause of sicknesses such as mesothelioma and asbestosis (Umweltbundesamt, 2022a; US EPA, 2023). The material is therefore not suitable for reuse but instead needs to be treated as toxic waste. While research on future asbestos outputs is important to estimate necessary specialised treatment capacities, the topic is outside the scope of this study due to its focus on future secondary material supply. The MI values consider the above-named materials in the main structural elements, roofs, facades, insulation and others, but for example not in MEP installations. The nine material classes are overarching terms for a grouping of several materials. Table A.1 in Appendix A includes a detailed list of all materials in the classes. The absolute values of the applied MIs per MI class and studied material are displayed in Appendix B, Table B.1. Figure 3.2 shows the absolute quantities of materials per m^2 of gross floor area (GFA) per MI class on the top and the respective contribution of individual material to the total value at the bottom.

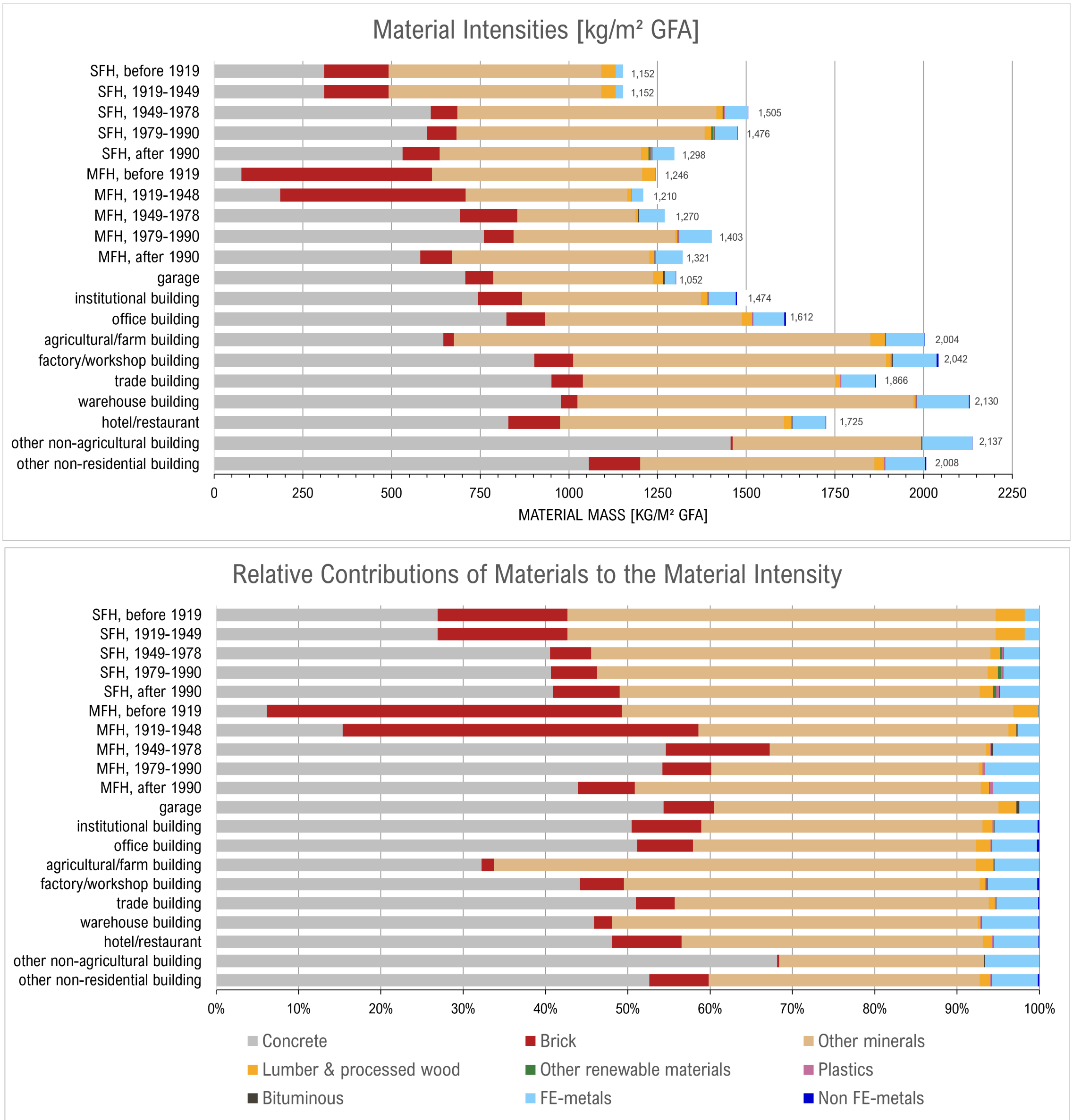

Figure 3.2: Top: Material intensities per MI class. Bottom: Contribution of different materials per class. Author's visualisation using values from (Haberl et al., 2021; IÖR, 2023) and own calculations.

As described before, the MI values base on synthetic building types, which are e.g. determined from data on blueprints. Thus, the values describe the original state of a building after construction and do not represent renovation activities that took place in the time between the construction of the building and the year of the analysis (e.g. the current year). For a certain period, it is reasonable to assume that renovation solely served to maintain the building in a similar state. However, in recent decades renovation measures add material to a building due to higher insulation requirements and multi-layered windows with higher amounts of glass. As mentioned before, Haberl et al. (2021) use the MIs from IÖR (2023) for the German part of their study. Next to that, they use MIs for Austria, determined by Lederer et al. (2021) for the city of Vienna. The latter considers renovation partially, looking at two factors: Extension of attics in buildings before 1946 and insulation of walls and roofs in buildings constructed before 1977. They also analyse whether wood-framed box-type windows have been replaced by PVC-framed windows in their sampled buildings. Comparing the German and Austrian MIs, the former are higher, despite neglecting changes through renovation, which is also not considered by Haberl et al. (2021). This raises the question of whether modelling past renovation activities on top of the German MIs is necessary. Thus, this research does not consider past renovation measures.

For garages, only minimal data on MIs is available. This research aims at improving data availability by a novel approach of calculating MIs based on a standard-sized garage with a construction type specific to Hamburg. I determine the characteristics of common garage construction types with the help of an expert in the field (R. Erps, personal communication, 12.10.2023) and a Google Street View exploration (Google Maps, 2023). This results in two predominantly present types: Garages with walls made from sand lime bricks with either plaster or a layer of clinker bricks. The final MI is calculated as an average of these two types and the MI used by Haberl et al. (2021), which covers lightweight garage types.

3.2. GIS Bottom-Up Building Stock Analysis

As mentioned in Section 2.1, this research conducts the GIS bottom-up building stock analysis by following the steps of the *The Geographic Approach*. The coloured boxes in the bottom row of Figure 3.3 display how the single steps of *The Geographic Approach* are applied to this analysis. For all steps that require the use of GIS software, I use *ArcGIS Pro*.

3.2.1. Ask

This research conducts a GIS bottom-up building stock analysis with the objective of answering sub-research question 2: *What are the current stocks of materials in buildings in Hamburg?*. The outcome of the study should be detailed data on the different material contents of individual buildings in the city of Hamburg. These numbers can then serve as an input to the dynamic MFA model.

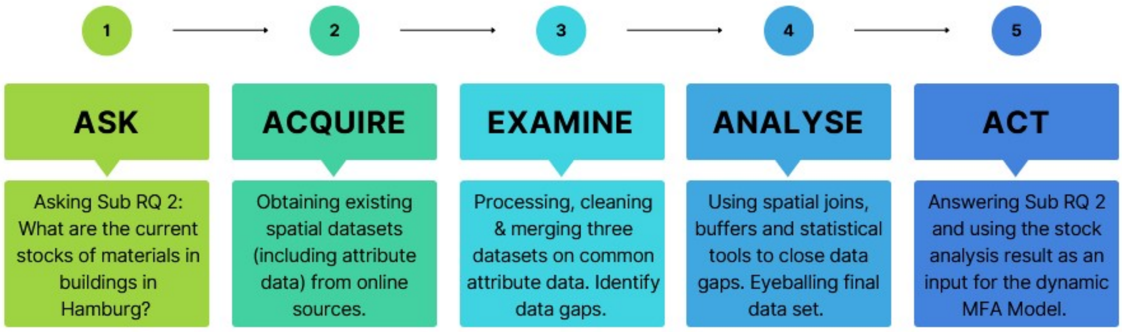

Figure 3.3: The Geographic Approach and its application to this research. Author's visualisation.

3.2.2. Acquire

Equations (3.1) and (3.2) describe how the material quantities in the building stock are generally calculated, indicating which kind of data is needed for the analysis.

The total mass of the stock M_{total} is the sum of the total mass per type of material $M_{total,tm}$. The total mass per type of material is the sum of the individual material masses per building $M_{b,tm,tf,a}$ in the stock. The material mass $M_{b,tm,tf,a}$ of a building *b* per type of material *tm* with a function *tf* and of age *a* is a materials' material intensity *MI* for function type *tf* and age *a* times the gross floor area (GFA). The material intensity indicates the amount of material that is present in an area of a certain size.

$$M_{total} = \sum M_{total,tm}$$

$$M_{total,tm} = \sum M_{b,tm,tf,a} \tag{3.1}$$

$$\text{with} \quad M_{b,tm,tf,a} = GFA_b\ [m^2] \times MI_{tm,tf,a}\ [kg/m^2]$$

The GFA of a building is the product of the surface area by the number of floors, counting floors above and below ground. This means the GFA includes all areas in a building that are enclosed by its outer walls, as well as the footprint of the outer walls themselves.

$$GFA = \text{surface area } [m^2] \times (\text{N° of floors above ground} + \text{N° of floors below ground}) \tag{3.2}$$

Based on these equations, the data to be acquired includes the number of individual buildings, as well as each building's surface area and number of floors. Further data requirements include the function and age of buildings, so that MIs, usually specified for different functions and age cohorts of buildings, can be applied. The material intensities are separately discussed in Section 3.1.

The study acquires the identified spatial and attribute data from existing datasets available on online platforms. The *Landesbetrieb Geoinformation und Vermessung (State Office for Geoinformation and Surveying)* is the city's institution dedicated to supplying spatial data. Furthermore, the federal states in Germany maintain a nationally standardised *Official Real Estate Cadastre Information*

System (ALKIS), which is run by the above-named state office concerning Hamburg. Based on this cadastre, I acquire two different datasets, which each contain required data. Unfortunately, no dataset complete with all the needed information exists, entailing the need to merge several data sets. Furthermore, I acquire a dataset on objects with monumental status, which contains additional data on the age of monuments in Hamburg. An overview and detailed description of the three acquired datasets are displayed in Table 3.1. The column 'relevant data content' relates to the data used for this analysis, meaning some datasets have more attribute data available, but are either less complete than other datasets or considered not relevant for this research.

Table 3.1: Description of the acquired data sources for the spatial and attribute data.

Number	Dataset name	Description	Relevant data content	Point in time	Format	Source
[1]	*INSPIRE Gebäude 2D ALKIS Hamburg*	This dataset includes the buildings of the Free and Hanseatic City of Hamburg taken from the Official Real Estate Cadastral Information System (ALKIS) and presented in the INSPIRE target model.	▪ building polygon (geometry) ▪ gml ID ▪ construction year	July 2020	.gml	https://metaver.de/trefferanzeige?docuuid=0C4AD3A9-ECC4-4936-92FD-18E21DFA9234
[2]	*Gebäude - Hamburg*	This dataset includes the outlines and additional federal state-specific data from the Official Real Estate Cadastral Information System (ALKIS). The file is published by the 'Landesbetrieb Geoinformation und Vermessung' (State Office for Geoinformation and Surveying) and originally provided by the 'Transparenzportal Hamburg' (Hamburg Transparency Portal). However, downloading was only possible from the German Esri website.	▪ building polygon (geometry) ▪ function type ▪ building type ▪ floors above ground ▪ floors below ground ▪ surface area [m^2]	April 2022	.shp	https://opendata-esri-de.opendata.arcgis.com/datasets/esri-de-content::geb%C3%A4ude-hamburg-1/about
[3]	*Denkmalkartierung Hamburg*	This dataset includes all objects with monumental status in the city of Hamburg (e.g. statues, historical border marks, tunnels, bridges, buildings, historical cemeteries etc.). It is published by the 'Behörde für Kultur und Medien, Denkmalschutzamt' (Department of Culture and Media, Office for the Protection of Monuments).	▪ building polygon (geometry) ▪ gml ID ▪ construction year	September 2016	.gml	https://metaver.de/trefferanzeige?docuuid=3B43E143-2C8B-43E8-8004-EE9EDA3EA563

3.2.3. Examine

The 'examine' step is the most time-intensive part of *The Geographic Approach*, as data exploration, cleaning, management and quality control involve many small steps. For readability reasons, this process is not explained in detail here, but Figure 3.4 displays how I merge data from the three acquired datasets into one file, which I then use for the data quality control and the analysis. The most relevant steps of the data cleaning and processing are described below, as well as important decisions I make in the process. For a more detailed visualisation, please refer to Appendix C, Figure C.1. Furthermore, the files submitted with this research include the generated code, in the format of Jupyter Notebooks, and the SI encompasses an accompanying detailed step-by-step guide, ensuring the reproducibility of this step.

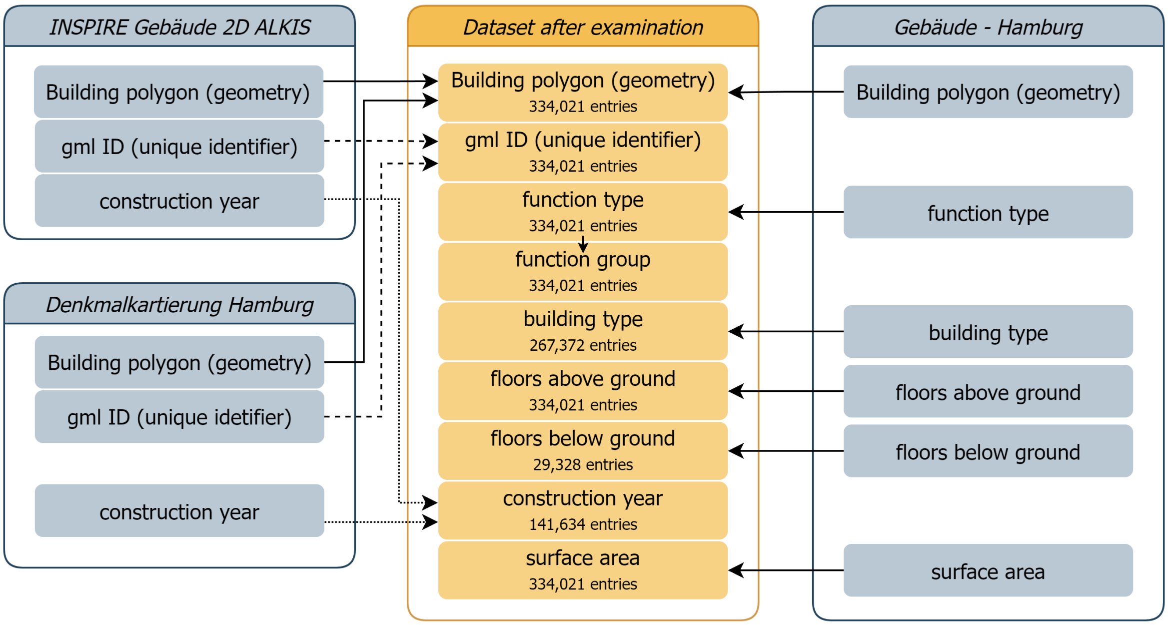

Figure 3.4: The outline of the dataset after the examination step. The arrows mark which dataset the data originates from. Author's visualisation.

During the first part of the examination step, I process, clean and lastly merge data. Some relevant steps and decisions I make during these steps are described below:

- Exclusions:
  - This analysis excludes the island of *Neuwerk*, which is a district of the City of Hamburg. As it is situated 100 km north-west of the city, it does not fit with the local-level scope of this research.
  - This analysis excludes objects with the function 'allotment_garden'.
- Relevant decisions:
  - Dataset [1] includes two layers 'Building' and 'Building parts'. The 'Buildings parts' layer includes polygons of building parts that have a different height than the rest of a building. Within the scope of this research, I only use the 'Building' layer and assume that in sum the lower and higher building parts compensate for each other, resulting in similar floor area data across the dataset.
  - Based on the data gap for construction years detected during data control, I decide to include dataset [3]. After identifying the data gap already early in the process, this is a first simple measure to enrich the present data with additional construction years.
  - As seen in Table 3.1 there is a slight time difference between the publication of the datasets. I define dataset [2] as a base, meaning the building polygons considered in this research are the most recently available ones. Buildings that are only present in dataset [2] therefore lack gml IDs, which I fill in by randomly generating IDs.

- Steps to highlight:
  - Datasets [1] and [3] include the 'gml ID', a unique identifier for every building in Hamburg. To maintain structure and a good overview of single objects in such large datasets unique identifiers are a very helpful tool. Using the 'Spatial Join' Tool in ArcGIS, I join the gml IDs to dataset [2], making it significantly easier to merge all data sets on this common identifier at the end of the exploration step.
  - Dataset [2] contains information on the function type of each building in Hamburg. This information is present in the form of standardised function codes, which I translate with the help of an *ALKIS object type catalogue* (AdV, 2018). This catalogue includes a standardised key for codes used in attribute data of spatial dataset. Appendix D, Table D.1 includes all function codes present in the dataset, their description in German and the English translation.
  - The different function types of dataset [2] are particular and do not have the commonly used labels of 'residential' or 'non-residential'. Therefore, I sort the function type categories into three main function groups: residential, non-residential and garages, as seen in Appendix E, Table E.1. I choose garages as a third function group in view of the fact that the number of entries for this function type is high and data completeness across all attributes is high as well.
  - Dataset [2] also contains data on building types of buildings in Hamburg, specifying whether buildings are for example detached, semi-detached or terraced. Like before, AdV (2018) serves as a tool to translate the standardised function codes in the acquired dataset. The types only relate to residential buildings and garages, meaning there are no building types in connection to non-residential buildings. Appendix F includes Table F.1 with all codes present in the dataset, their description in German and the English translation.

After merging the cleaned and processed files into one dataset, I test the data quality. Looking at the state of the dataset in Figure 3.4 again, three attribute categories stand out lacking data: 'building type', 'floors below ground' and 'construction year'.

The 'building type' column, which relates to residential buildings and garages, has 267,372 entries, while the two function types together count 291,739 objects, meaning the data is 91.6% complete. This gap is handled in the analysis step.

There is no method available to fill the data gap in the 'floors below ground' column. The largest part of the available data relates to residential buildings, namely 93.28%. Only 6.46% and 0.26% relate to non-residential buildings and garages, respectively. In total, only 8.8% of buildings have records in the number of floors below ground. Nevertheless, I decide to use the present records albeit not complete. Plotting a histogram (see SI) of the number of residential buildings with data on basements next to the total number of residential buildings shows that the data is approximately equally distributed, except for the years after 2010, where basements are better documented than in previous years. If an overestimation of floor space in residential buildings is detected, those years are especially sensitive.

The data gap for the 'construction year' column poses the biggest challenge, being only 42.2% complete. This gap needs to be filled not only for applying age-specific MIs in the stock analysis but also for the data to serve as input to the MFA model. I decided to apply a GIS-based allocation method developed by Jenis (2023), which is explained in detail in the analysis step.
Finally, I test the accuracy of the data for the following relevant columns.

Construction Years

Random samples from online real estate advertisements of apartments (ImmoScout24, 2023; immowelt, 2023), which often include building construction years, serve as points of comparison for the values in this column. A list of the samples can be found in the SI. Looking at 25 samples, 88% of the objects show a maximum deviation of two years between the acquired data and the real estate advertisements. 8% show a deviation between 2 and 10 years and 4%, meaning one sample, has a deviation greater than 10 years. In conclusion, I assume the construction year data to be accurate enough for the given research objective. The reliability of the construction year data in general is mediocre due to it not being complete, as already discussed above.

Floors Above Ground

I validate the values for floors above ground through a comparison with height data and a visual check. Very recently, *Geoportal Hamburg* published a 3D Model in *Level of Development 3 (LoD3)* on their web-based application (Landesbetrieb Geoinformation und Vermessung, 2023; Stadt Hamburg, 2023). It allows for displaying a realistic visual appearance of buildings, making it possible to count floors by eye. In addition, the LoD2 layer can be activated, which contains height data. By comparing height data and also checking the visual appearance of random samples, I evaluate the data accuracy for the number of floors above ground. The SI contains a documentation of the random samples.

Firstly, the comparison shows that for residential buildings with flat roofs the number of floors in the acquired data matches with the visual appearance. The same applies to the assumed height (one storey = 3 meters) and actual height data. For residential buildings with gable, hip or jerkinhead roofs the number of floors matches the visual appearance if there is no floor in the attic. For buildings with floors in the attic, the data is not accurate, as the top floor is often, but not always, missing. This naturally results in a high difference between the assumed height derived from the number of floors and the actual height. Furthermore, many residential buildings do not have a true ground floor but a mezzanine floor, which adds to the deviation. For non-residential buildings, the number of floors in the acquired data is accurate when compared to the visual appearance. However, the assumed height often deviates from reality as storey height is found to be very specific to different non-residential functions. Deriving the actual height from the number of floors in hall constructions is complicated, as they usually consist of very high storeys specific to their use requirements. Furthermore, buildings serving a public purpose, such as educational institutions or commercial spaces, often feature storeys higher than three meters.

In conclusion, I find the data on the number of floors to be accurate, except for residential buildings with the top floor in the attic. Nevertheless, the data remains unchanged. Instead, I decide to use the data in this state and compare results with available statistics. Depending on the outcome of this comparison, appropriate measures could be taken to adapt the data. Concerning the comparison of height data with the number of floors, I find that mezzanine floors and different roof types limit correlations between these two units of measurement for residential buildings. The same applies to non-residential buildings due to their unique characteristics.

3.2.4. Analyse

At this point, two main tasks are left before calculating the total building stock of Hamburg, using equation (3.1): Filling the gap in construction year data and sorting all buildings in MI classes that correlate with the available MIs.

Construction Year Data

The acquired data for construction years of residential buildings, non-residential buildings and garages is distributed as seen in Figure 3.5. For the purpose of visualisation, the data is displayed per age cohort here. As mentioned before, the data gap is large and thus requires a suitable approach to be filled.

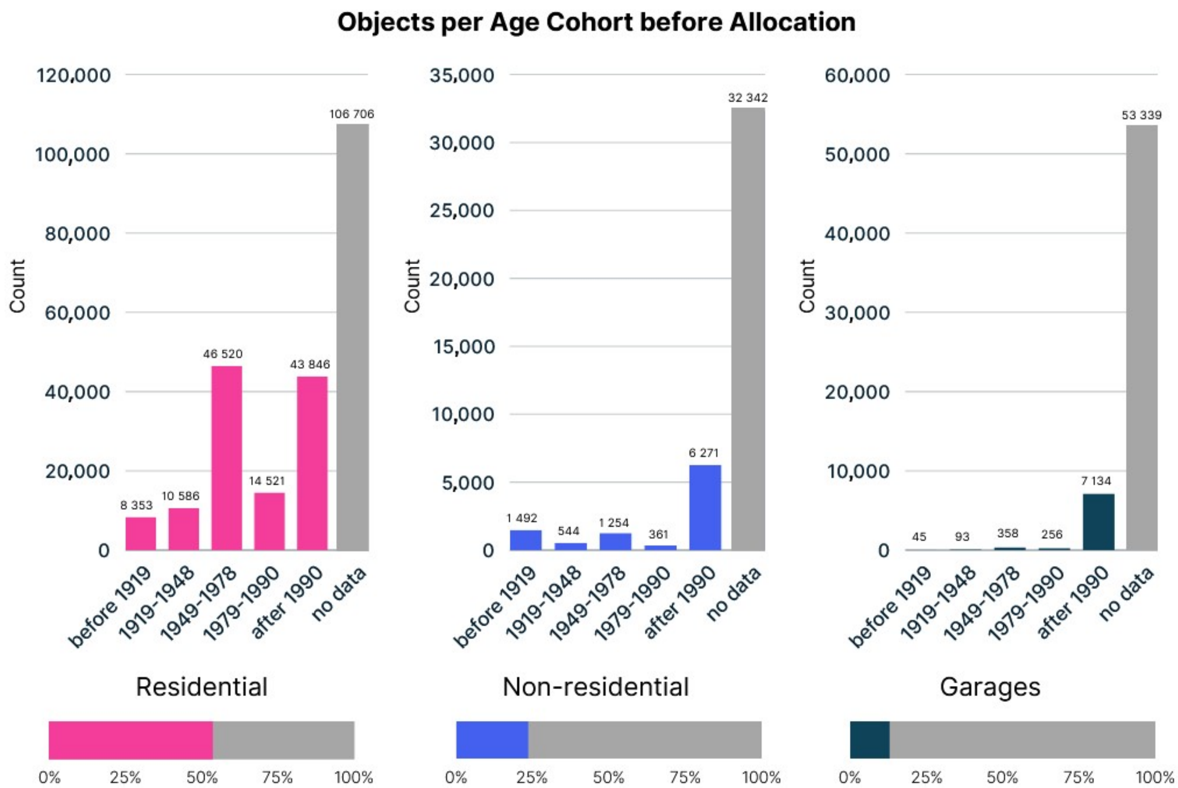

Figure 3.5: Comparison of the data count distribution per age cohort for the three function groups. Author's visualisation.

I adapt and apply an allocation process developed by Jenis (2023). This approach allocates available construction year data from one building to another one, that is lacking this data, based on proximity and through multiple rounds of iteration. I perform this allocation in ArcGIS and provide a detailed step-by-step guide on this process in the SI.

By putting a buffer of a certain size around a building lacking data, I detect nearby buildings with data and allocate their data via the buffer to the building. If multiple construction years are available for allocation, the one with the highest occurrence is chosen. Figure 3.6 visualises the allocation schematically. I increase the buffer size for the next iteration step if only a small number of construction years is allocated in the previous step. Tables I.1, I.2 and I.3 in Appendix I display the buffer choices per function group and the number of allocated construction years per round of iteration. The three function groups are treated differently to consider their individual characteristics.

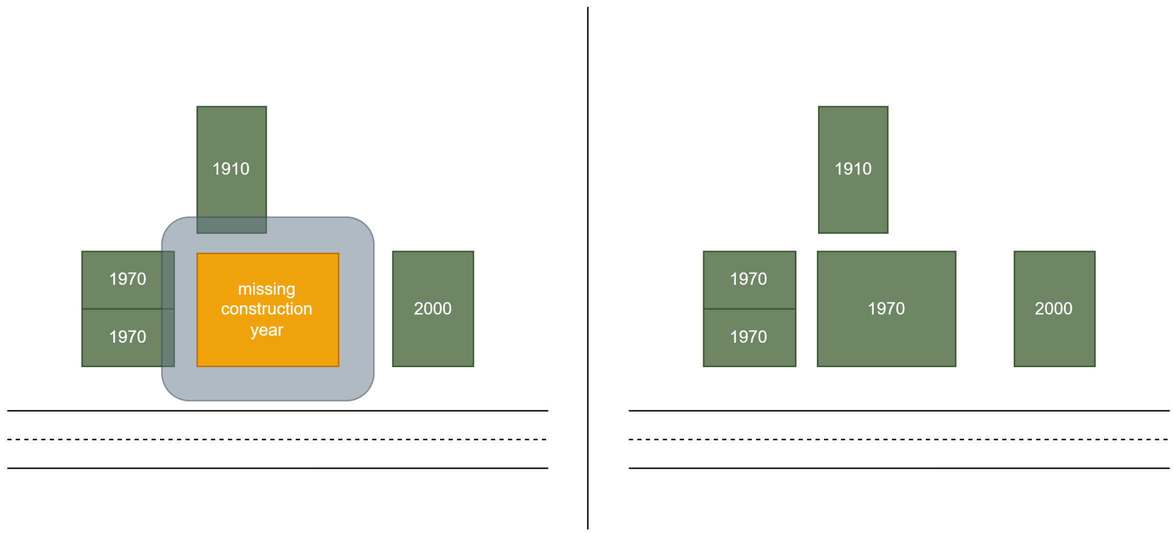

Figure 3.6: Schematic visualisation of the construction year allocation method. Author's visualisation based on (Jenis, 2023).

For residential buildings, I allocate construction years from other residential buildings. During the first rounds of iteration, I keep buffer sizes small, to ensure that for example in rows of terraced houses, where the construction year of one building is known, data is allocated to all houses in that row and not from other nearby buildings. In general, I set the threshold at which I increase the buffer size to min. 1% improvement per iteration but do not use the same buffer size more than three times. I determine the increase in buffer size by examining randomly selected objects in ArcGIS that are still missing years of construction and comparing them with buildings in the neighbourhood that could possibly assign their years, then measuring the distance between them. All details of the iteration steps for allocation can be found in Table I.1 in Appendix I.

For non-residential buildings, I first allocate construction years from other non-residential buildings only. After the 15th iteration step I determine with the help of visual inspection that most of the non-residential buildings in the vicinity of other non-residential buildings have been assigned their year of construction. Thus, starting from the 16th iteration, I allocate construction years from residential and non-residential buildings. From visually checking the buffer sizes, I determine to increase the buffer size whenever less than 1500 buildings get a construction year allocated in one iteration step. In comparison to residential buildings, I increase the buffer size in larger steps, as non-residential buildings are more spread out and further away from each other. How much the buffer size is increased I again determine by visual checks.

As visualised in Figure 3.5 very little construction year data is present for garages and most of them are individual objects that are often associated with residential or non-residential buildings. Therefore, I allocate construction years to garages from residential and non-residential buildings. This means, that in contrast to the two other allocation processes, garages that get a construction year allocated in one iteration will not allocate that year to other garages in the next step. Thus, I use every buffer size only once, allocating all possible data in one step for that specific buffer size. Naturally, I increase buffer sizes quickly, again based on visual checks.

Material Intensity Classes

Lastly, I sort buildings into classes correlating with the acquired material intensities. For residential buildings, I utilise data on building types. As seen in Table G.1 in Appendix G, I label all high buildings with more than four floors are as multi-family houses (MFH), as well as all buildings lower than four floors that are either terraced or detached blocks. Browsing these types on Google Street View shows that the data is accurate and these buildings are indeed 'blocks' housing multiple apartments. For the three other types, individual detached, semi-detached and terraced houses, I find the data to be only partially accurate. Thus, using Google Street View and my knowledge of the city, I re-categorise the three types into SFH and MFH by determining and applying surface area limits. In some cases, they might seem quite high to the external observer, but this is due to Hamburg being a sprawled-out city and some typical SFH building styles having quite generous floor plans. Residential buildings with no building type value make up 9.6% of all objects in this function group and I label them as SFH or MFH based on surface area limits. Non-residential buildings already have very precise function data, which I use to sort them into the nine MI classes defined by the MI categories, as seen in Table H.1 in Appendix H. In the sorting process, I also integrate additional information on these non-residential MI classes available on the website of IÖR (2023).

Stock Calculation

Using equation (3.1), I finally calculate the stock of the different materials in every building and consequently for the total of Hamburg.

3.2.5. Act

The obtained results of the bottom-up building stock model can be found in Section 4.1. The data furthermore serves as input to the dynamic MFA Model.

3.3. Dynamic Material Flow Analysis

The bottom-up dynamic MFA model models the maintenance of Hamburg´s building stock on the level of individual buildings. This includes the renovation of buildings, their demolition and consequential replacement construction. Expansion of the building stock lies outside the scope of this research. The model is stock-driven, using the results of the GIS bottom-up stock analysis as inputs and the characteristics of the individual objects in the stock as drivers of demolition and renovation activity. The MFA system is visualised in Figure 3.7. So far, studies working with granular GIS-based data for MFA modelling aggregate the building-level data either by floor space per year (Heinrich, 2019), grid cells (Han et al., 2018) or regions (Heeren & Hellweg, 2019). In contrast, this research maintains the granular resolution and prospects the future dynamics of individual buildings in Hamburg's building stock.

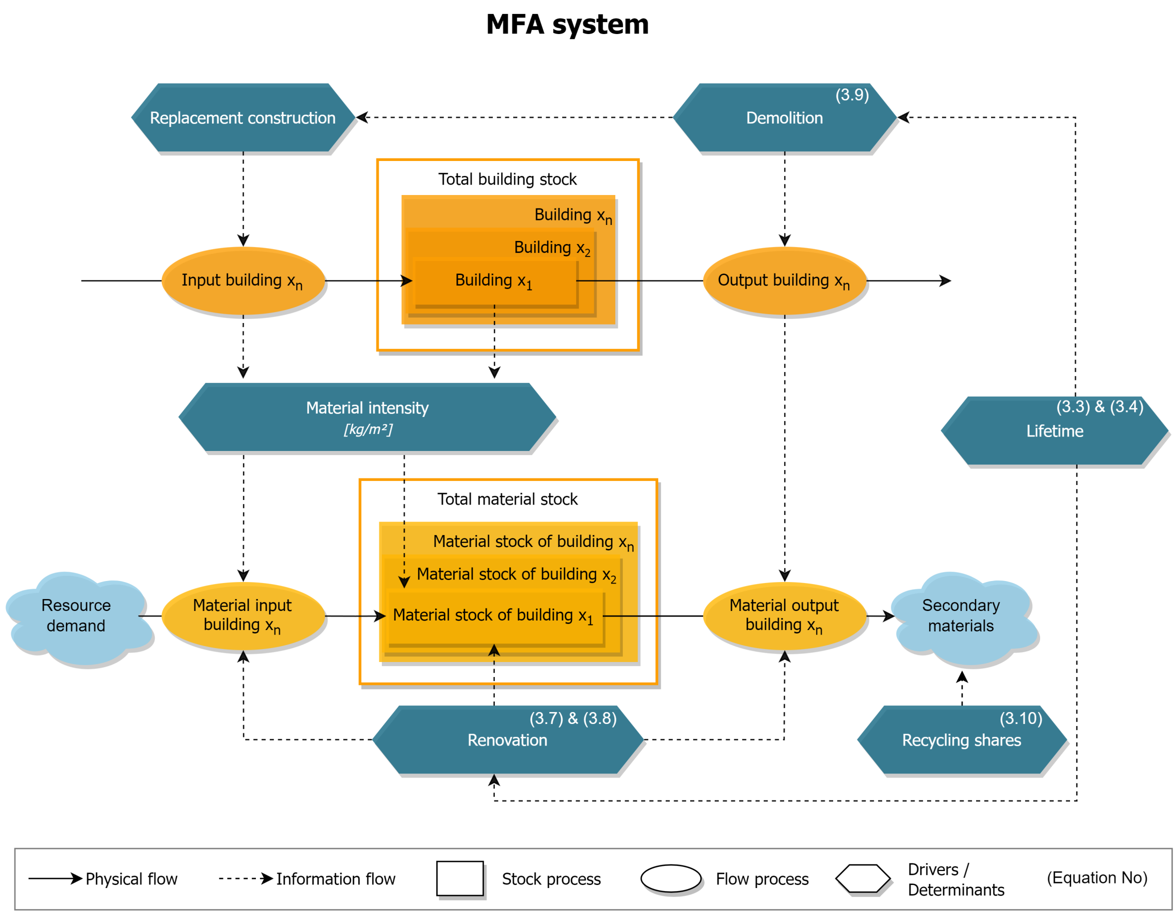

Figure 3.7: Schematic visualisation of the MFA system. The depicted equation numbers relate to the ones given in the following subsection. Author's visualisation.

3.3.1. Building and Material Stock

Determined by the GIS bottom-up stock analysis, the data on Hamburg's building stock serves as an input to the model. The individual buildings contain the data on function, age and GFA, which act as a base to apply MIs and calculate the material stock.

I adapt the time scope of the building stock data to include all buildings with construction years between 1800 and 2018. The most recent construction year in the stock analysis, 2019, has significantly fewer objects than prior years. While this could depict reality, I ascribe this fact to the commonly present time lag in official data. As the datasets used for the GIS analysis were published in 2020, it cannot be guaranteed that the last year before publication is correctly documented. Thus, the MFA model only considers building stock data up to and including 2018. I decide to exclude the buildings from years before 1800 (9,800 out of 344,021), as their lifetime characteristics are hard to predict (partially also due to monumental status) and being so few in numbers, I do not expect them to be significant to calculations.

The following subsections describe the different parameters influencing the dynamics of the buildings and the materials contained therein. I, again, emphasise that I generate parameters unique to individual buildings, based on their age characteristics and MI class.

3.3.2. Lifetime of Buildings

Modelling the lifetime of buildings or dwelling space for MFA purposes is usually done by sampling from probability density functions of e.g. normal distributions (Bergsdal et al., 2007; D. Müller, 2006; Sartori et al., 2008) or Weibull distributions (Heeren & Hellweg, 2019; Miatto et al., 2019; Sartori et al., 2016).

For this study, the construction year for every single building object in the current stock is either known or allocated by the author as described in Section 3.2. Based on this data availability, I decide to sample the building lifetime from a truncated Weibull probability density function (PDF). A truncated Weibull PDF is a function that is truncated at either a minimum or maximum value, or both. Unlike the standard Weibull PDF, which takes two parameters, namely shape (k) and scale (λ), as seen in (3.3), the truncated Weibull PDF takes additional parameters for a left limit (U_L) and right limit (U_R), see (3.4). Miatto et al. (2017) find Weibull distributions to perform well for non-residential buildings and mention that right-skewed distributions generally better reflect the low probability of a building being demolished very shortly after construction.

$$f(x;\lambda,k) = \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e^{-(x/\lambda)^k} \quad , \ x \geq 0 \tag{3.3}$$

$$f(x;\lambda,k,a,b) = \frac{\frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e^{-(x/\lambda)^k}}{e^{-(a/\lambda)^k} - e^{-(b/\lambda)^k}} \quad , x \geq 0 \qquad \text{where } a = \frac{U_L}{\lambda} \text{ and } b = \frac{U_R}{\lambda} \tag{3.4}$$

Similarly to the study by Heeren and Hellweg (2019), this study requires building lifetime sampling for the buildings in stock at the time of sampling. Demolition probability for surviving buildings changes over time, which is represented by sampling from a truncated Weibull PDF (Heeren & Hellweg, 2019). The truncation thereby ensures that buildings present in the stock of 2018 are not demolished before the year 2018. The left limit for values drawn from a Weibull PDF must therefore always be the difference between 2018 and the construction year of a building Y_C, as seen in (3.5).

$$U_L = 2018 - Y_C \tag{3.5}$$

There is no need for truncation on the right side of the Weibull PDF, hence $U_R \to \infty$ and therefore $b \to \infty$. For $b \to \infty$ follows $e^{-(b/\lambda)^k} \to 0$ and the equation for the (left) truncated Weibull PDF can be simplified to (3.6).

$$f(x;\lambda,k,a,b) = \frac{\frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e^{-(x/\lambda)^k}}{e^{-(a/\lambda)^k}} \quad , x \geq 0 \tag{3.6}$$

It should be noted, however, that the above-displayed simplification is only serving the purpose of comprehension and that the function *scipy.stats.truncweibull_min* used in the Python model requires the input of a and b, even for a one-sided truncation, which is why I set b to ∞.

Besides a and b, the shape (k) and scale (λ) parameters are inputs to the Weibull distribution. The shape parameter determines the shape of the curve, with k = 3 approximating the shape of a standard distribution. Concerning building lifetime calculations, the shape parameter can be interpreted as a measure of change in the risk of an asset being demolished, with a shape value $k > 2$ reflecting a progressively increasing risk of demolition. The scale parameter determines the distribution's variability. High scale parameters lead to a curve with low height and stretched out to the right, while low scale parameters lead to high and compressed curves.

I determine the shape and scale parameters used in this research considering multiple estimations of average building lifetimes (Bergsdal et al., 2007; Heeren et al., 2015; Kohler & Yang, 2007). I also account for the fact that the old buildings in the stock have longer lifetimes than the more recently constructed ones (Kohler & Yang, 2007), by choosing changing average lifetime values for defined cohorts. In general, accurate data on building lifetimes is scarce, specifically for non-residential buildings. For garages, no data is available to my best knowledge, thus, I decide to treat them like residential buildings. The assumed average lifetimes, standard deviation and corresponding parameter values can be found in Table 3.2. In Appendix J, Figures J.1 and J.2 display the application of these values, determining the truncated Weibull PDF and the distribution of random samples for four different construction years as an example.

Table 3.2: Lifetime parameters for the Weibull distribution. Average lifetime and standard deviation are given in [years].

	Construction Period	**Shape (k)**	**Scale (λ)**	**Average Lifetime**	**Standard Deviation**
Residential Buildings and Garages	<1875	3	168	**150**	54.52
	1875-1924	3	165.75	**140**	50.87
	1925-2018	3	140	**125**	45.44
Non-Residential Buildings	<1875	3	168	**150**	54.52
	1875-1924	3	165.75	**140**	50.87
	1925-2018	3	112	**100**	36.35

3.3.3. Renovation

Following an adaptation of the approach of Sartori et al. (2016), I model renovation based on the characteristics of the building stock and the stock's required maintenance over time. I draw the length of one renovation cycle as a random value from a normal distribution, see equation (3.7), with the following values for the mean (μ) and standard deviation (σ):

- residential buildings: $\mu = 30$ years, $\sigma = 7.5$ years
- non-residential buildings: $\mu = 20$ years, $\sigma = 5$ years
- garages: $\mu = 40$ years, $\sigma = 10$ years

Plots of the normal distribution for the listed parameters are displayed in Appendix K, Figure K.1. I define these mean values based on a comparison of different renovation cycle estimations from papers in relation to Europe or Germany (Sandberg et al., 2016; Sartori et al., 2008; Sartori et al., 2016; Schiller et al., 2015; Umweltbundesamt, 2022b). This research assumes that garages have slightly longer renovation cycles than residential buildings, which are usually estimated to be renovated every 30 to 40 years. Furthermore, this research does not differentiate between small renovation measures and deep renovation, which is mostly estimated to occur every 40 years. Therefore, I choose $\mu = 30$ years for residential buildings, to resemble more frequent renovations with lower impact. Non-residential buildings usually have shorter renovation cycles due to frequent tenant changes often resulting in renovation activities. Thus, they are renovated more frequently. I assume a standard deviation of 0.25μ based on Sartori et al. (2008) and apply it to all function groups.

$$\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{1}{2}(\frac{x-\mu}{\sigma})^2} \tag{3.7}$$

The number of renovation cycles per building depends - next to its function - on its lifetime. Furthermore, a building that is renovated in one year is very unlikely to be demolished the next. This means that the time between the demolition year of a building and the last renovation cycle is always longer than the length of the average renovation cycle $R_{cycle,\mu}$ in this model. Therefore, I only draw random values for the renovation cycle length from the standard distribution as long as the sum of the construction year and all renovation cycles up to that point is smaller than the demolition year minus the average renovation cycle length $R_{cycle,\mu}$, see equation (3.8).

$$Y_{Constr} + R_{cycle,1} + R_{cycle,2} + ... + R_{cycle,n} < Y_{Demo} - R_{cycle,\mu} \tag{3.8}$$

According to Umweltbundesamt (2022b), the material flows resulting from renovation amount to 5.5% of a building's material mass for inflows and 5% for outflows. Hence, a slight growth of the material stock in a building of 0.5% is registered, which can for example be explained by additional insulation materials being installed. Furthermore, Umweltbundesamt (2022b) mention that the share of materials within the above-mentioned in- and outflows should be adapted to account for the fact that structural parts of a building (mainly made from concrete or other minerals) usually stay in place during renovation, while windows are exchanged more frequently or insulation is only added, but not removed. However, modelling e.g. these thermal renovation processes in detail is outside the scope of this research. For research objectives more specific to insulation materials or glass, however, the modelling of renovation in- and outputs should be adapted.

3.3.4. Demolition

This study uses a simplified approach to demolition dynamics. Other studies account for a so-called *retirement period* or *disuse* (Sartori et al., 2016) where buildings are not immediately demolished when reaching the end of their service life, but become hibernating stocks. In contrast, this research assumes that buildings are demolished in the year they reach their determined lifetime. The demolition year Y_D, is determined by the year of construction Y_C and the lifetime L sampled from the truncated Weibull distribution, see equation (3.9). Although I include data on buildings with monumental status, I assume that all buildings will be demolished at some point. Based on personal experience, I can state that buildings with monumental status are sometimes demolished in Hamburg, hence it is a reasonable assumption to not exclude them from demolition modelling.

$$Y_D = Y_C + L \tag{3.9}$$

When a building is demolished, all materials in its stock, including the materials added by renovation activities over the years, become outflows in the demolition year.

3.3.5. Replacement Construction

Within the model, I assume that every demolished building is replaced by a building of the same size and with the material intensity of the most recent age cohort *after 1990*. However, the latter only applies to residential buildings as MIs for garages and non-residential buildings do not differentiate between age cohorts. The replacement construction is taking place in the year after demolition, introducing a minimal but reasonable time lag. The material inflow resulting from replacement construction only includes the materials determined by the MIs, i.e. the material that is required for the building's construction and neglects additional materials such as construction site waste generated during the construction process.

After construction of the replacement building, I sample a new lifetime from a Weibull PDF without truncation, as seen in Equation (3.3). The truncation is no longer needed as I now determine the lifetime at the point of construction and not retrospectively, as before. The shape and scale parameters correspond with the ones used for the most recent construction years, as seen in Subsection 3.3.2. The Weibull PDF is displayed in Appendix L, Figure L.1. Based on the determined lifetime, the model assigns a new demolition year and new renovation cycles, sampled from a normal distribution with the same parameters described in Subsection 3.3.3.

3.3.6. Secondary Material Supply

The final outflows of materials determined through MFA modelling can partially be recycled. Reuse is outside the scope of this research, due to the reasons explained in Section 2.6. Losses occur during the collection and processing of the outflow materials, for example, due to imperfections in sorting or systemic losses due to the physical properties of materials. Therefore, I determine secondary material supply from recycling by deducting the specific losses per material from the correlating total outflows, see equation (3.10). The values for the share of losses are given in Table 3.3. These ratios must be understood as a strong simplification due to the reasons explained in Section 2.6.

$$M_{secondary,tm} = M_{out,tm} - M_{out,tm} * share_{loss} \tag{3.10}$$

Table 3.3: Collection and processing losses of recyclable materials occurring during demolition and recycling processes.

	Collection and Processing Losses of Recyclable Materials	Source
Concrete	15%	(Heinrich, 2019; Verhagen et al., 2021)
Bricks	25%	(Heinrich, 2019)
Other minerals	15%	(Heinrich, 2019)
Lumber & processed wood	5%	(Heinrich, 2019; Verhagen et al., 2021)
Other renewable materials	10%	(Heinrich, 2019)
Plastics	10%	(Heinrich, 2019)
Bituminous	50%	(Heinrich, 2019; Verhagen et al., 2021)
FE-metals	5%	(Heinrich, 2019; Verhagen et al., 2021)
Non FE-metals	5%	(Heinrich, 2019; Verhagen et al., 2021)

4

Results

4.1. GIS Stock Analysis Results

4.1.1. Construction Year Allocation

The allocation of construction years results in the age cohort distribution visualised in Figure 4.1. For non-residential buildings, most objects were built in the age cohort *after 1990*. In comparison with the initially known values (see Figure 3.5), the distribution maintains a similar shape throughout the allocation. The cohorts *before 1919* and *1949-1978* are small but larger than cohorts *1919-1948* and *1979-1990*, while the most recent cohort is the largest.

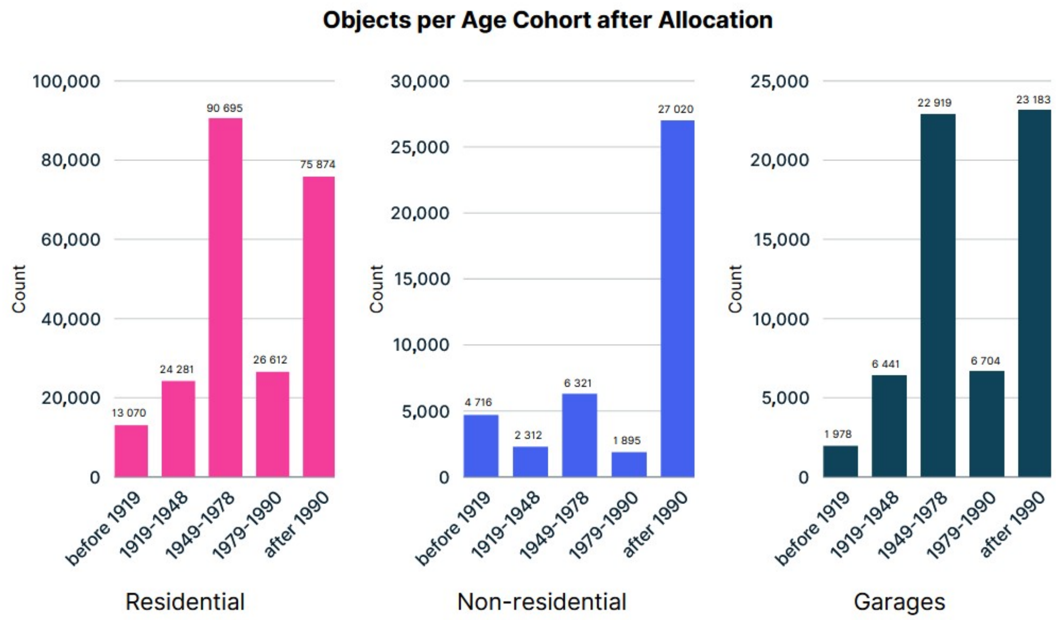

Figure 4.1: Number of objects per age cohort after construction year allocation.

For residential buildings and garages, the cohorts *1949-1978* and *after 1990* include the most objects. In comparison with the initially known values for residential buildings, the distribution maintains a similar shape, while it changes drastically for garages. Originally, less than 15% of garages have construction year values, with most of them in the *after 1990* cohort. After allocation, there are almost as many construction years in the *1949-1978* cohort as in the *after 1990* cohort.

I validate the allocation results with census data from 2011, which includes data on the number of residential buildings per age cohort. Unfortunately, there are no statistical records for non-residential buildings or garages. Figure 4.2 shows a comparison of the distribution of residential buildings across the five age cohorts. The allocation overestimates the most recent age cohort by approx. 9%. Furthermore, it very slightly overestimates the *1979-1990* age cohort and underestimates the three earlier cohorts, each by approx. 3-4%.

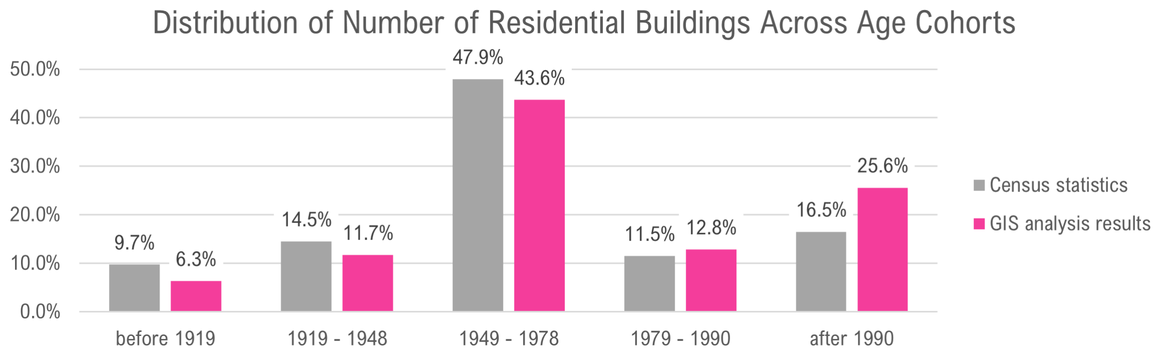

Figure 4.2: Comparison of statistical data and the GIS analysis results for the distribution of residential buildings across age cohorts. The last cohort only includes data until the end of 2010.

4.1.2. Building Stock Floor Area

Considering the small uncertainties in floor level data detected in Subsection 3.2.3, I consult official statistic records to validate the total floor area obtained through the GIS analysis. For residential buildings, data on useful floor area (UFA) until and including 1990 is available in the *Mikrozensus 2006* (small census done in between usual 10-year intervals). For the most recent cohort, I acquire data from the *Statistisches Jahrbuch*, a yearly report published by Hamburg's statistical office. As the GIS analysis returns results for gross floor area (GFA), I convert the values to UFA by applying conversion ratios specific to the age cohorts, which I derive from information on UFA and GFA by IÖR (2023), as displayed in Table 4.1.

Table 4.1: Useful floor area share in the gross floor area, derived from (IÖR, 2023).

Age Cohort	before 1919	1919-1948	1949-1978	1979-1990	after 1990
UFA Share in the GFA	72%	74%	77%	78%	81%

The comparison reveals that this analysis overestimates UFA for the *1949-1978* cohort, although the number of buildings in that cohort is underestimated, as stated in the previous subsection.

For all other cohorts, this research under- or overestimates UFA values similarly to the number of buildings. According to the official statistics the total UFA for residential buildings in Hamburg amounts to 71,667,610 m^2, while the result from the GIS analysis amounts to 78,746,438 m^2.

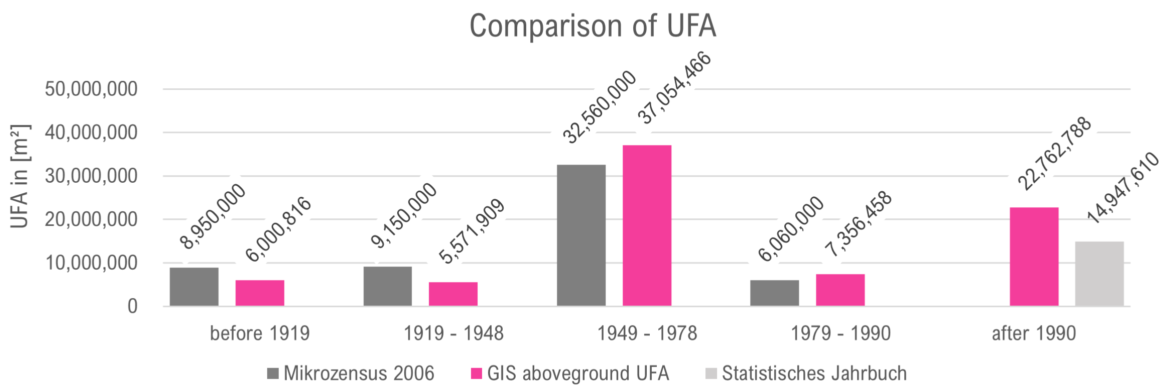

Figure 4.3: Comparison of useful floor area (UFA) per age cohort from statistical data and from the GIS analysis results. The last cohort only includes data until the end of 2010.

4.1.3. Materials

Answering sub-research question 1, this research determines the total stock of materials in Hamburg's building stock at 0.28 Gt. Figure 4.4 visualises the distribution of materials across the three function groups. The distribution of materials is similar between residential and non-residential buildings, with residential buildings containing 3.97 Mt more material. Garages account for only 1.3% of all materials in the stock, namely 0.004 Gt.

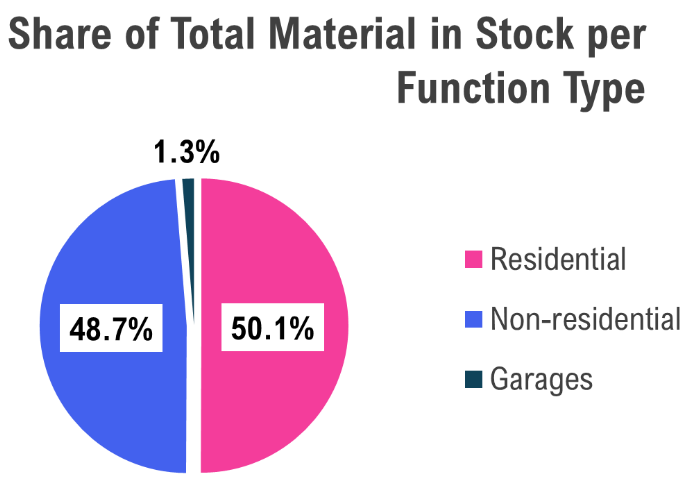

Figure 4.4: Share of materials in the building stock in Hamburg by function group.

Zooming in on the materials, Figure 4.5 displays the share of single materials in the stock. 47% and 37% of all materials in the stock are concrete and other minerals, respectively. Bricks make up 9% of the stock, FE-metals 5%. Lumber and processed wood account for approximately 1% and other renewable materials, plastics, bituminous materials and non FE-metals contribute less than 1% of the total material mass.

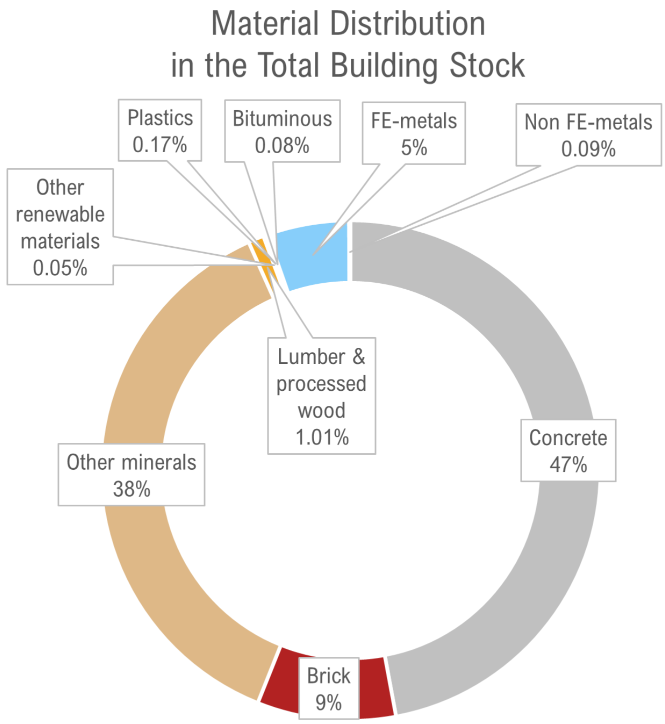

Figure 4.5: Contribution of the nine materials to the total stock.

Zooming in further on the results of the three function groups, Figure 4.6 gives some interesting insights in the overall context. While garages make up 18% of the objects in the building stock of Hamburg, their total GFA only amounts to 1% of the total stocks GFA. Furthermore, they only contain 1% of the total determined stock. Non-residential buildings show opposing characteristics. While making up only 13% of the objects in the stock by numbers, their total GFA accounts for 40% of the total GFA in stock and even 49% of all materials. Residential buildings are the largest in number, as they occupy 59% of the GFA and contain half of all materials in the building stock.

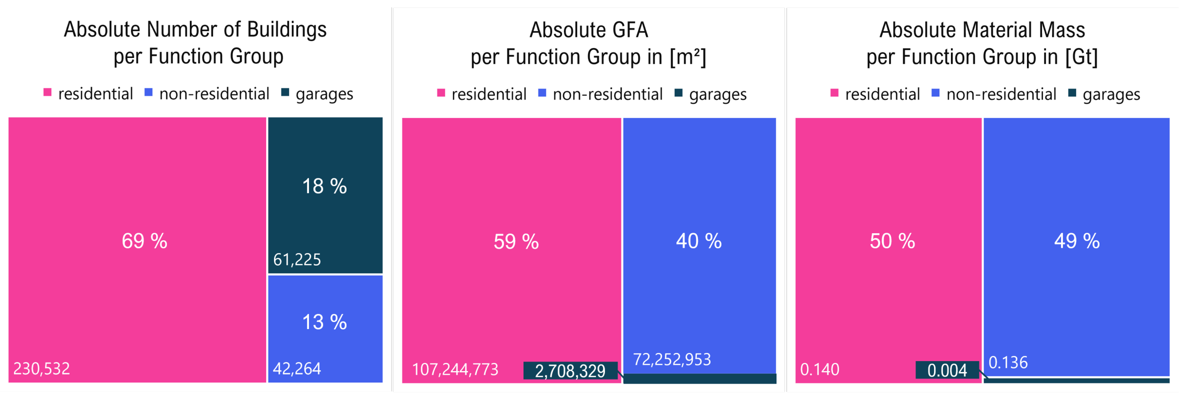

Figure 4.6: Treemaps comparing the absolute number of buildings, the absolute GFA in [m^2] and the absolute mass in [Gt] per function group.

Considering these findings on the relation between the number of buildings and the amount of contained material, Figure 4.7 gives more insight into the stock of materials in individual MI classes in relation to building numbers. This figure visualises nicely that for example the total stock of materials in *SFH, 1949-1978* and *SFH, after 1990* is significantly smaller than in *MFH, 1949-1978*, although both SFH cohorts contain more than twice the number of buildings of the MFH cohort. Furthermore, the figure once more underlines that garages contain little material, although they occur in large numbers. The figure also highlights how material-intensive office, factory/workshop, trade, warehouse, other non-agricultural and other non-residential buildings are. All of these classes include a small number of buildings compared to most residential classes but contain more materials than most of them.

Figure 4.7: Top: Number of buildings per MI class. Bottom: Material mass of the individual materials in [kt] per MI class.

Figure 4.8 visualises the relation between materials on the left and the 'end-use' (here: MI class) on the right. This visualisation again underlines the large stock of materials in MFH built between 1949 and 1978. Although the concrete intensity for this cohort is lower than in the class for MFH, 1979-1990, for example, the highest proportion of concrete is present in this MI class. This is also due to the fact that it encompasses the most objects of all MFH classes. It should also be mentioned that a large proportion of the brick is found in this class. The most material-intensive non-residential types are office and trade buildings, both with a larger share of concrete and other minerals.

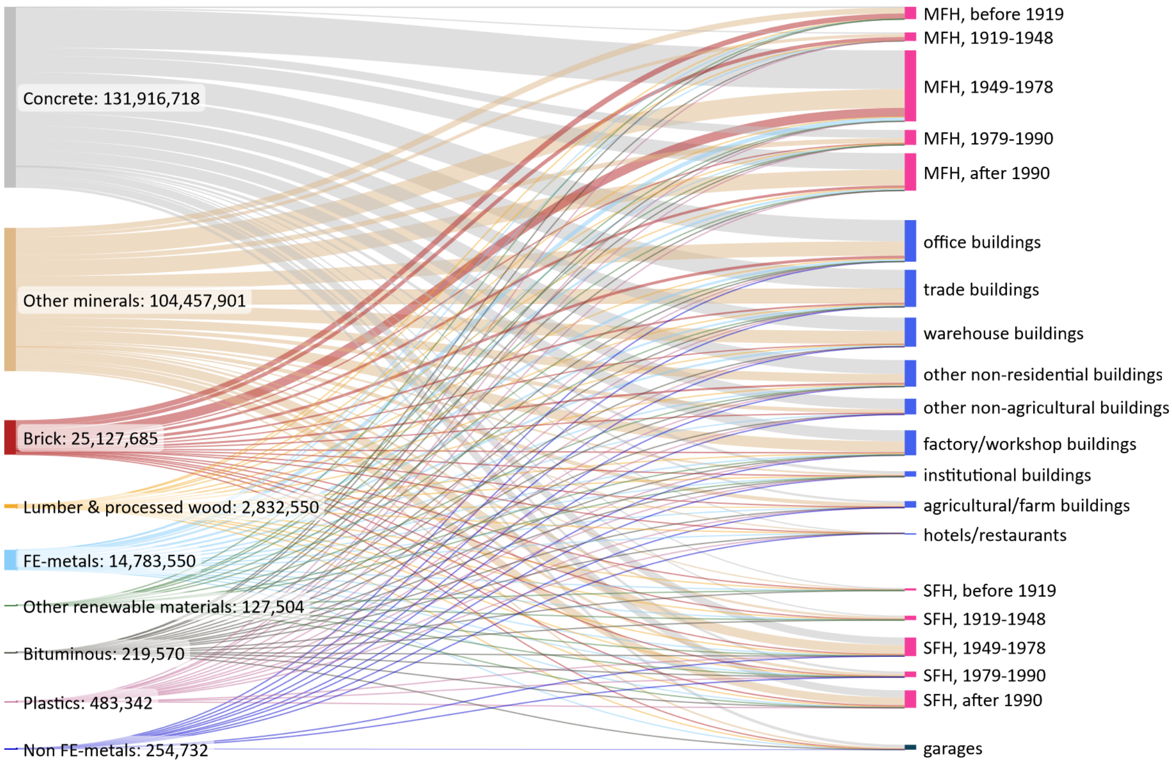

Figure 4.8: Sankey diagram showing the distribution of materials in the buildings stock of 2018 across the MI classes. Masses in [t].

4.1.4. Spatial Distribution

The spatial distribution of materials is visualised in Figure 4.9, which displays the absolute material mass in tons per 10,000 m^2. Material accumulation is high in the city centre (1) and the half-circle surrounding the centre (2). Towards the south, another area of similarly high accumulation can be detected, which aligns with the centre of the district of *Harburg* (3). This district evolved independently and only belonged to the city of Hamburg since 1938, still exhibiting some characteristics of an independent town, such as its own small city centre.

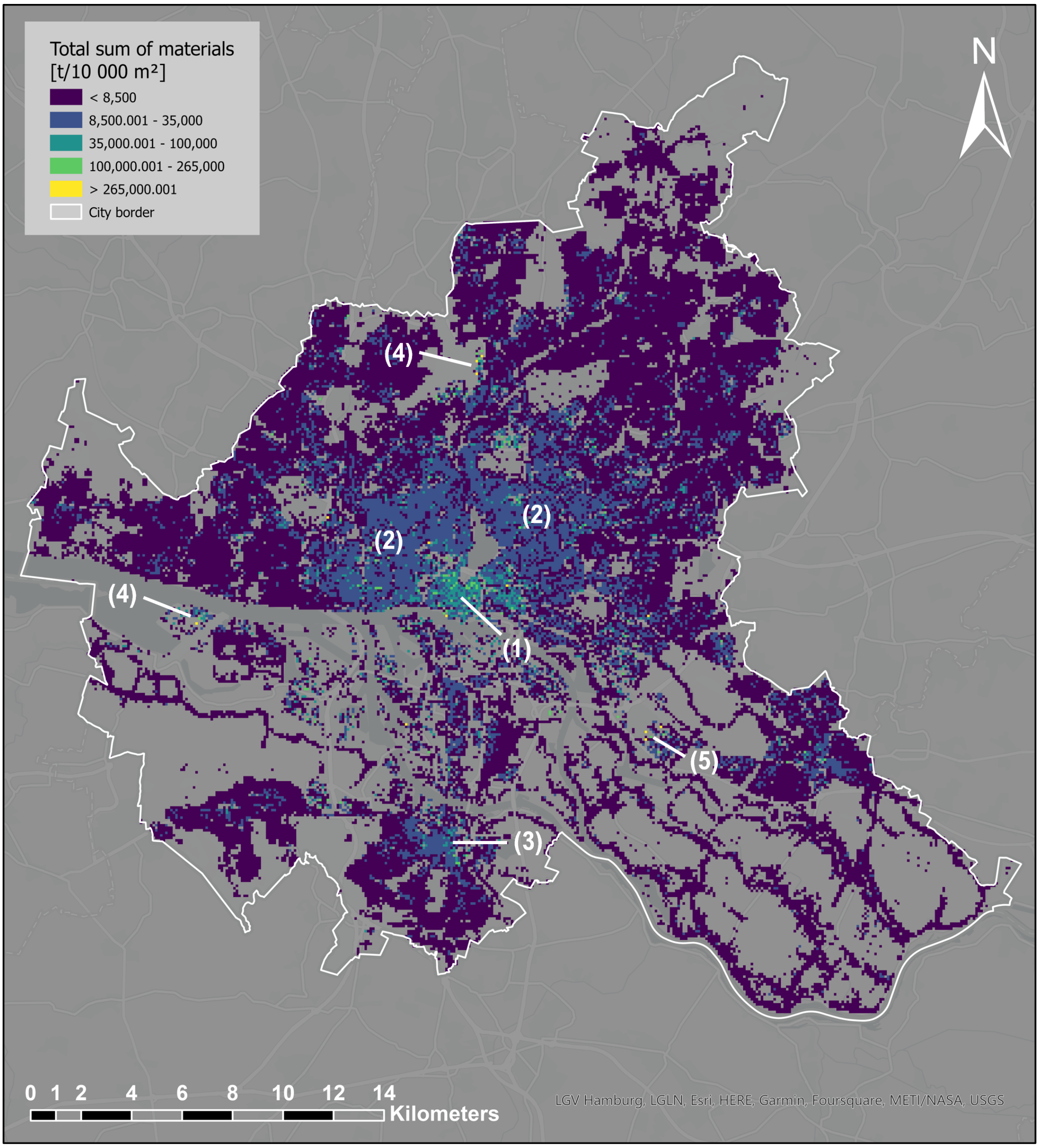

Figure 4.9: Spatial distribution of the absolute material stock in buildings in Hamburg.

Other areas of high material accumulation can be detected when zooming into the map, where there are yellow raster cells. In the centre north and centre west, two areas of very high material accumulation are found at the location of the two airports of Hamburg (4). Furthermore, there are multiple cells of high material accumulation in the lower mid-east of the city, which marks a large industrial area (5). In general, material accumulation is found to be higher in areas that overlap with non-residential functions. For comparison, a map with the spatial distribution of the three function groups can be found in Appendix N, Figure N.1. The comparison also shows that low material accumulation corresponds with the residential areas along the outskirts of the city. Furthermore, Appendix O, Figure O.1 displays the spatial distribution of SFH and MFH in

Hamburg. A comparison with Figure 4.9 shows that material density is high in areas where MFH are predominantly found, while density appears to be lower in areas with mainly SFH.

Overall, material is more densely accumulated in the northern half of the city of Hamburg. In the south-eastern tip of the city, material accumulates along lines, showing the agricultural characteristics of this area, where buildings are mostly located along streets and areas in between are agricultural land. Similar characteristics are exhibited by the area in the southwest of Hamburg, right below the river *Elbe*. Material also appears to be accumulating in a more scattered shape right below the city centre, which is the port area, dominated by water.

4.2. Dynamic MFA Model Results

4.2.1. Renovation and Demolition Activity

The projected renovation and demolition activity between 2019 and 2075 is visualised in Figure 4.10. The number of renovated buildings per year increases from 2019 until it reaches a peak around 2035. Activity then slowly decreases and seems to almost stabilise after 2060. Analysing the predominant age cohorts undergoing renovation until 2035 (see Figure 4.11), I find that the most recent age cohort is driving the number of renovations per year to its peak levels. Buildings from this age cohort do not reach the end of their lifetime, yet, but are predominantly renovated. The number of demolished buildings per year, as seen on the right side of Figure 4.10 increases continuously until 2075. The post-war age cohort of *1949-1978* accounts for the largest share of buildings being demolished over the entire considered time frame. The number of demolitions per year for the two oldest age cohorts steadily decreases, but still makes up for 20% of buildings being demolished in 2075. Demolition activity for the most recent cohort increases over time, accounting for roughly 20% in 2075 as well. Starting around 2050, demolition activity also occurs for the replacement constructions. Across the three studied function groups residential, non-residential and garages the share of each function in the total number of renovated and demolished buildings per year is relatively constant over time. For a visualisation please refer to Appendix P, Figure P.1.

In 2020, the renovation rate is approximately 2.3% and 2.6% in 2035. After 2060 it almost stabilises around 2.2%. The demolition rate develops from 0.3% around 2020 to 0.55% in 2050 and 0.75% in 2075.

Respecting the spatial nature of the input data to the MFA model, it is interesting to also look at the location of building demolition. Figure R.1 in Appendix R visualises the locations of all buildings to be demolished until 2030. I choose this time frame, as it is the period in which only buildings present in the current stock are demolished but not yet any of the replacement buildings. The locations of to-be-demolished buildings are relatively evenly distributed across the city. However, most demolitions occur in the city centre and in a small circle around it. Southwest of the city centre two larger structures can be seen, which are non-residential buildings.

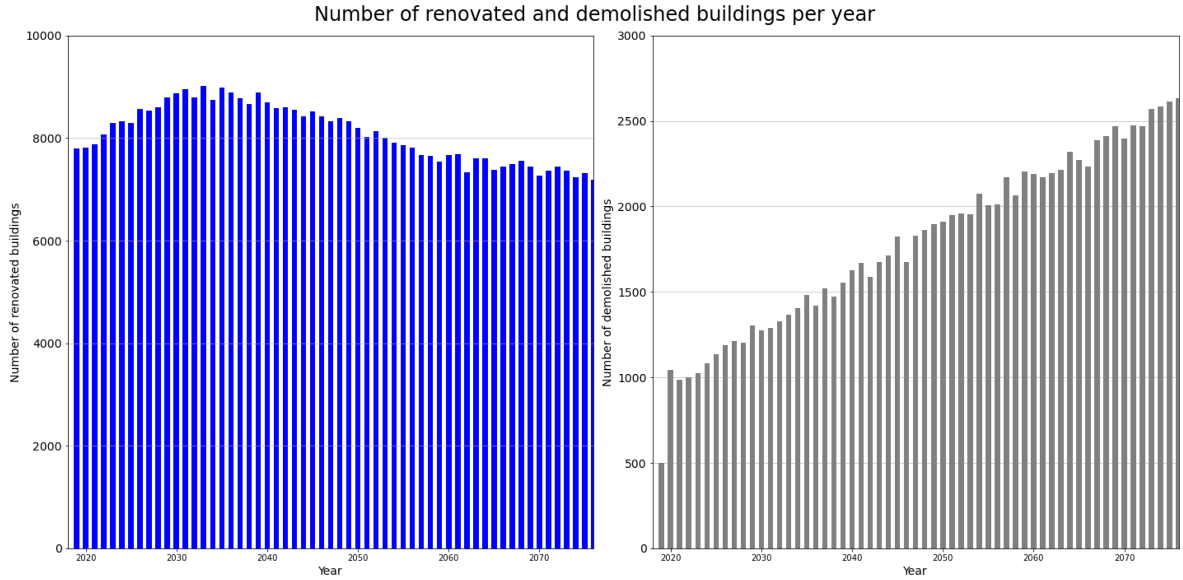

Figure 4.10: Number of buildings renovated (left) and demolished (right) per year until 2075.

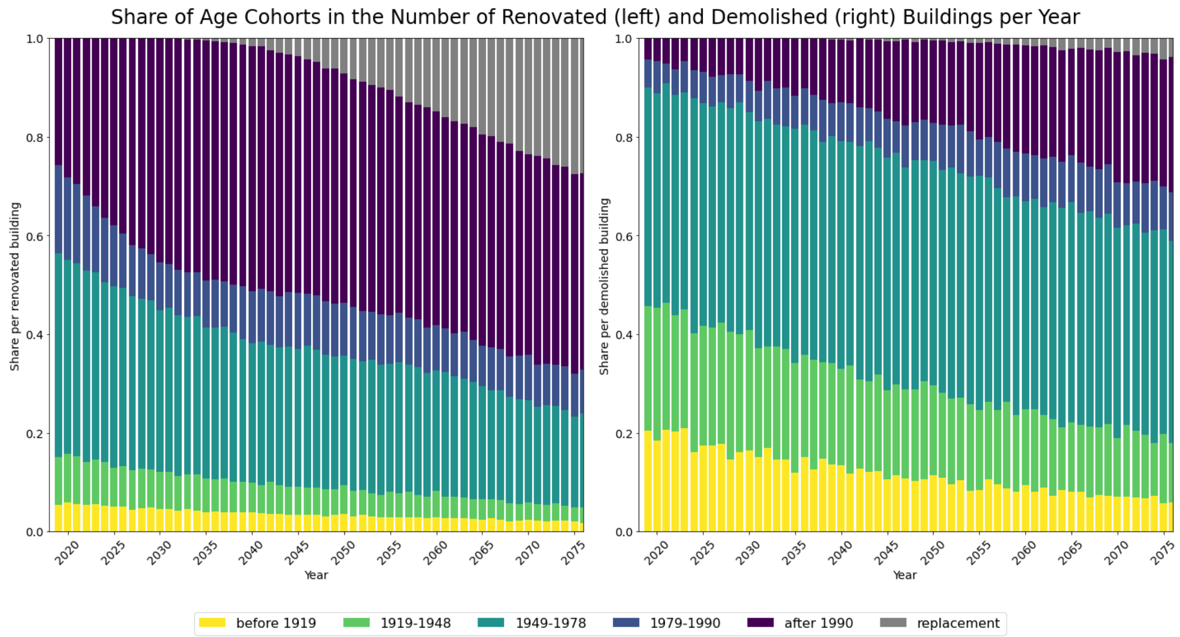

Figure 4.11: Share of age cohorts in the number of renovated (left) and demolished (right) buildings per year

4.2.2. Material Mass Results

Answering sub-research questions 2 and 3, Figures 4.12 and 4.13 display the prospected total outflows and inflows over time until 2075, respectively. Both figures show a split, with the bulk materials in the top pane and the non-bulk materials in the bottom pane, due to the difference in magnitude in their values. The outflows for concrete, other minerals and lumber & processed wood increase over time. A very slight increase can also be detected for FE-metals, plastics and bituminous materials. The outflows for bricks, Non-FE-metals and other renewable materials are more or less stable over time.

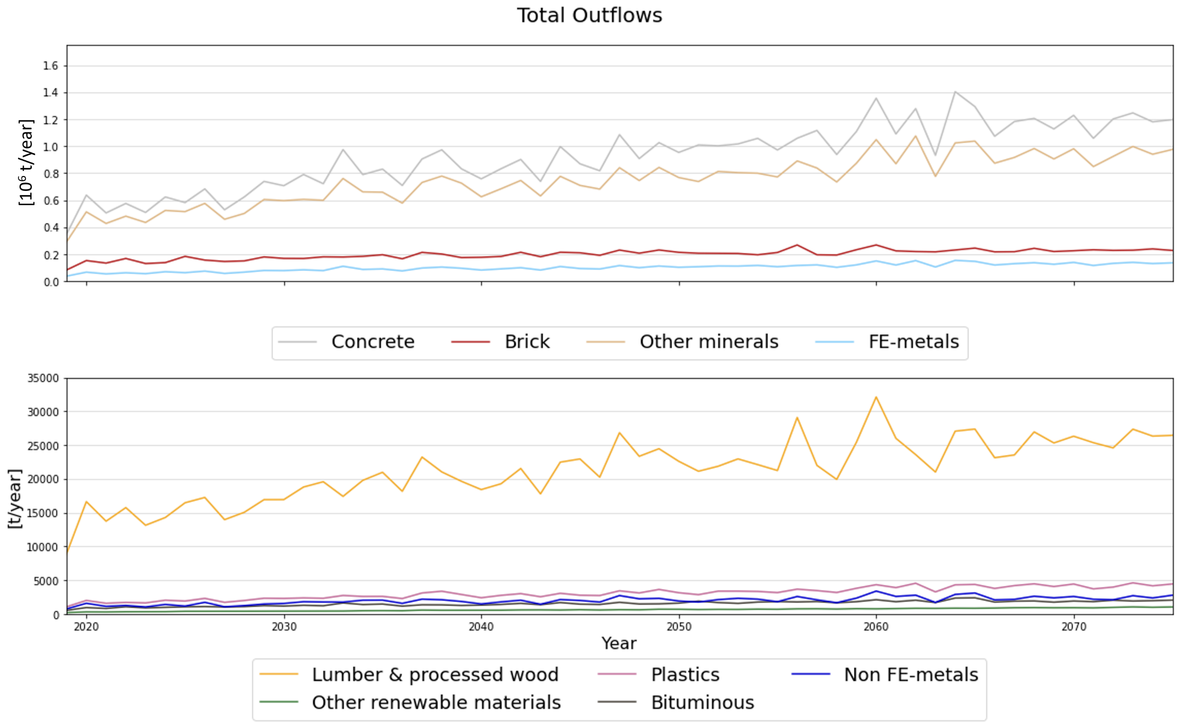

Figure 4.12: Total outflows until 2075. Top: Bulk materials. Bottom: Non-bulk materials.

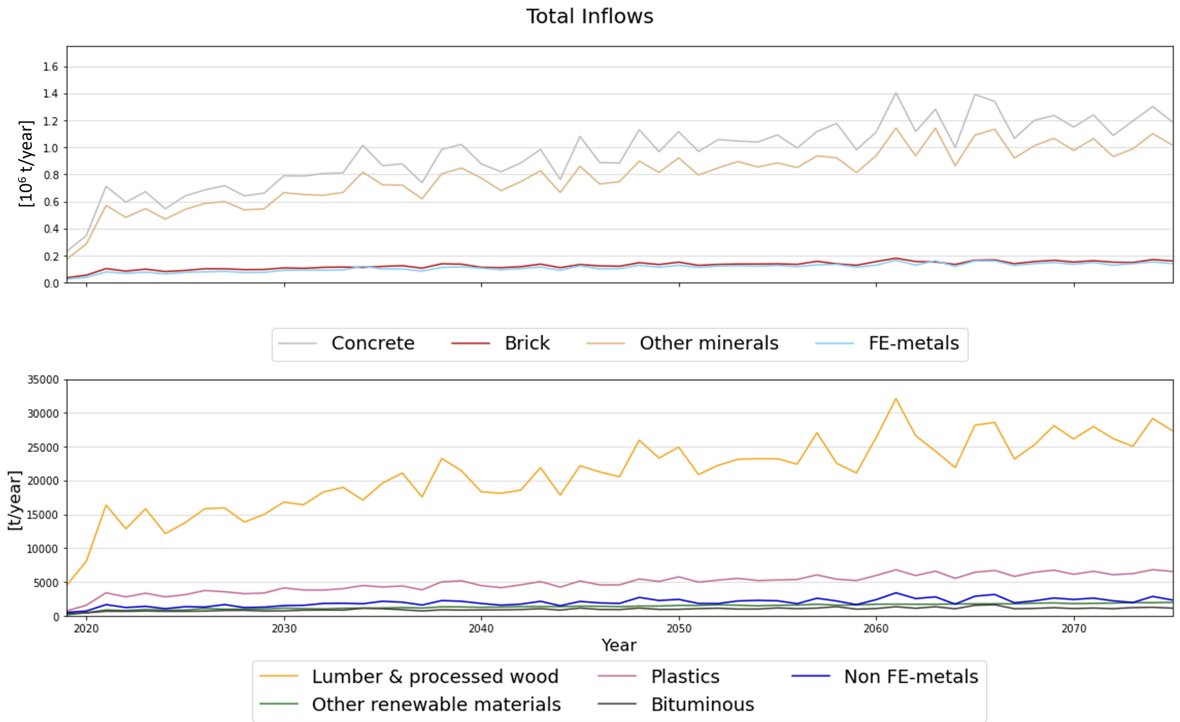

Figure 4.13: Total inflows until 2075. Top: Bulk materials. Bottom: Non-bulk materials.

The inflows of materials are shifted in time, caused by the one-year time lag, when demolished buildings are replaced. For most materials, the inflows are of similar magnitude as the outflows, with an exception for brick and plastics. The mass of future brick inflow is roughly half the mass of brick outflow. For plastics, this is reversed, as plastics inflow is generally higher over the considered period than plastics outflow.

As mentioned, the material inflows are mainly shifted in time but do not differ drastically from the prospected outflows. This relates partially to the impact of demolition and replacement construction in comparison to the impact of renovation activities. Figure 4.14 highlights the significant impact of outflows from demolition on the total outflows. In comparison, outflows from renovation activity are small. Hence, the shape and size of the total material outflows are mainly determined by material outflows from demolition, while the total material inflows are mainly determined by the material required for replacement construction.

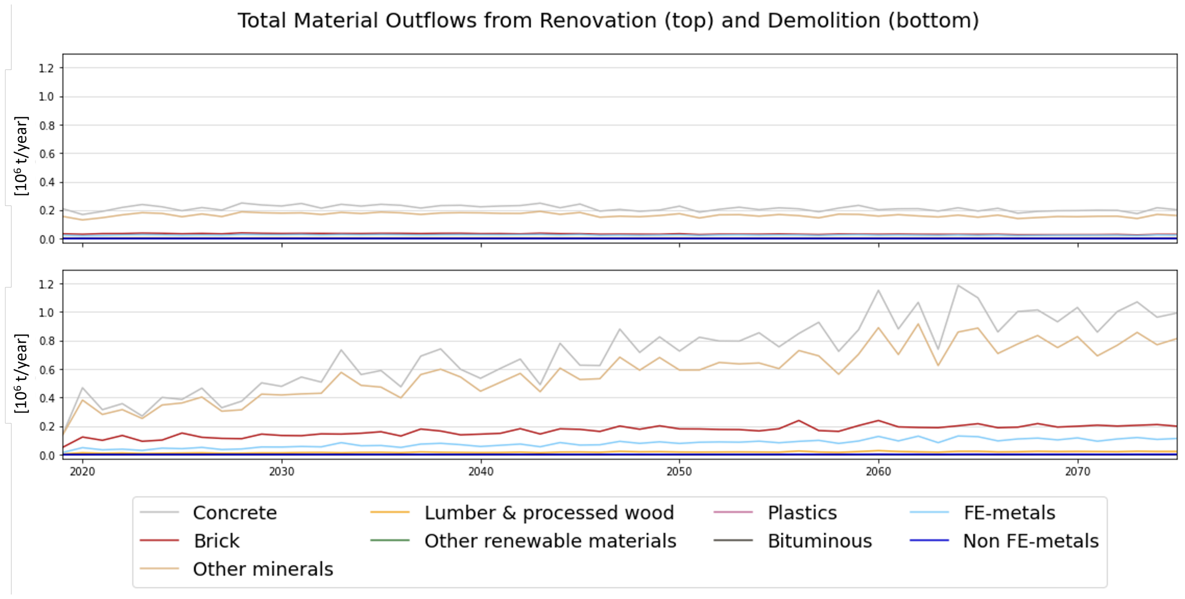

Figure 4.14: Total material outflows from renovation (top) and demolition (bottom) until 2075. The scale of the y-axis is deliberate, displaying the difference of the outflows in size and their resulting influence on the total outflows.

Zooming in on the impact of different function groups on future material in- and outflows, I find the following. Garages show very small contributions to the total in- and outflows over time. In general, their material flows are approximately 20-30 times smaller than flows from residential buildings. The impact of material in- and outflows for non-residential buildings determines the general shape of the total in- and outflow curves and contributes a large share of material mass (Appendix Q, Figure Q.1 and Q.2). However, the difference in in- and outflows is - again - mainly the shift in time. Besides the aforementioned reason, the second factor causing this shift is the following: As I model non-residential buildings and garages with the same material intensities over the considered time frame, inflows from replacement construction correspond with the outflows from demolition. Thus, the inflow curve appears to be shifted in time.

In contrast, residential buildings exhibit different material intensities over time and I model replacement construction utilising the most recent MIs. Figure 4.15 shows the impact of this approach. The future brick inflow only corresponds to half of the brick outflow. Furthermore, the future inflows for concrete and other minerals are almost the same, while the outflow of other minerals is smaller than for concrete, especially after 2050.

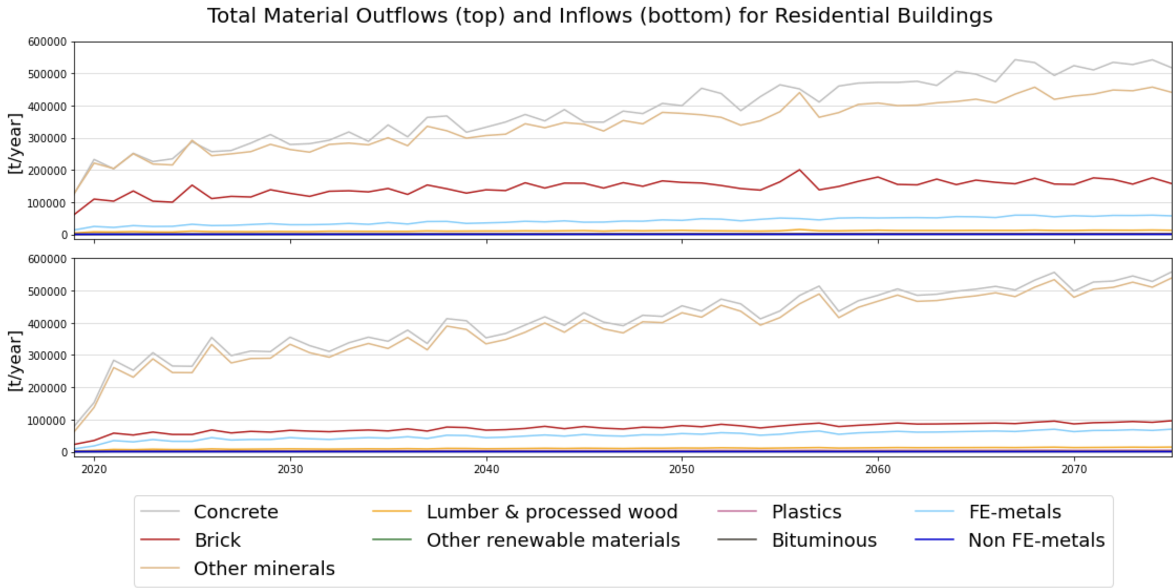

Figure 4.15: Total material outflows (top) and inflows (bottom) for residential buildings until 2075.

Results for Secondary Material Supply

Answering sub-research question 4, I calculate the secondary material supply for three periods, namely 2019-2025, 2026-2050 and 2051-2075, by applying the shares of material losses during recycling as explained in Subsection 3.3.6. For each of the chosen periods, Figure 4.16 displays the total outflows and the derived available secondary material supply, which is compared with the demand for material in that period. A negative mismatch of 11%, 17% and 16% is identified for the periods of 2019-2025, 2026-2050 and 2051-2075, respectively. A more detailed investigation of the single materials results in the identification of brick being the only one case, where demand could be fully covered by secondary material supply. Overall, the potential for brick demand to be covered by secondary material is higher than for other materials, as more brick becomes available than is required in the long run (Figures 4.12 and 4.13). This holds true, although losses during brick recycling are relatively high in comparison to other materials, with the exception of bituminous materials (see Table 3.3).

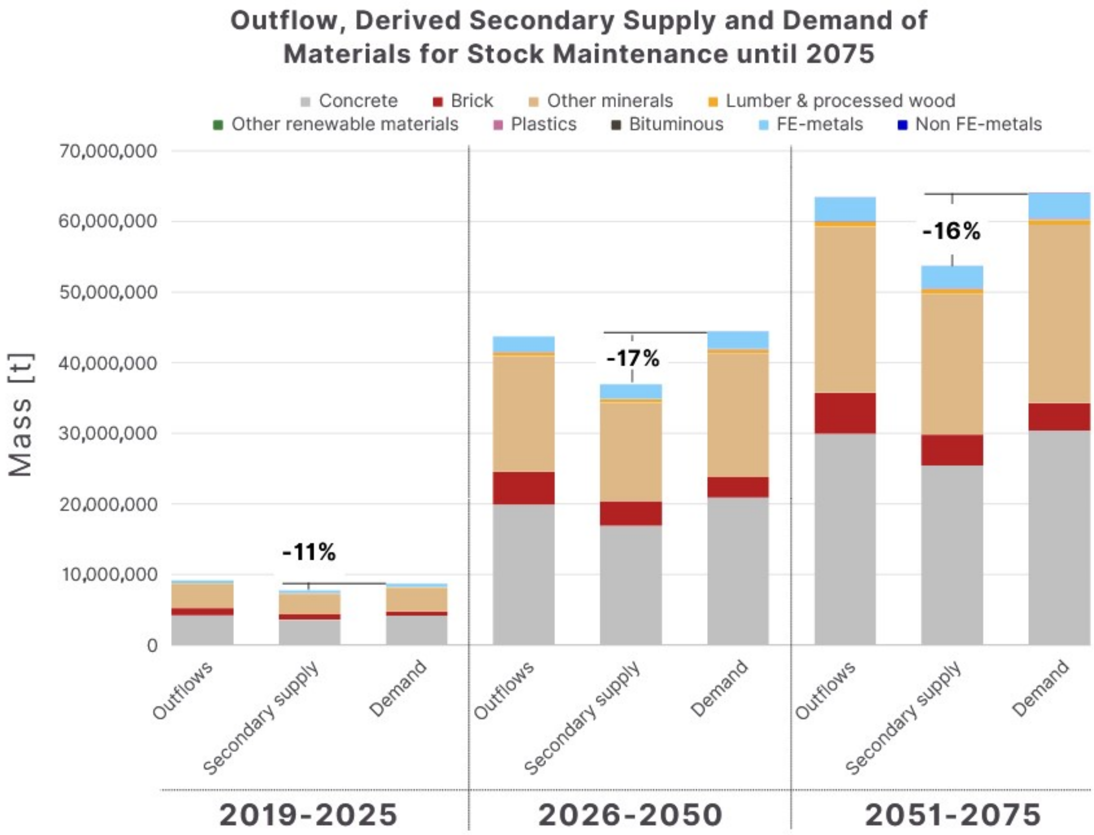

Figure 4.16: Comparison of total outflow, available secondary material and total material demand in the periods of 2019-2025, 2026-2050 and 2051-2075.

5

Discussion

The first part of this chapter encompasses the discussion of the results and their related implications. The second part focuses on the discussion of the methods and data as well as their limitations. It also gives recommendations for future application of the methods utilised in this research.

5.1. Discussion of the Results

This section sets obtained results into context, validates them with prior research and elaborates on the implications arising from these results. Furthermore, answers to sub-research question 5 are given throughout this section.

Stock Analysis Results

Setting the results of this research's stock analysis into context, results from prior research serve as points of comparison. Various studies obtain results on material stocks in Germany, that can either be translated for comparison or even include spatially differentiated results with readily available values for comparison on e.g. federal state level. Some studies obtain results for other cities or regions, that are compared on a per capita basis. Table 5.1 provides an overview of how the results of this GIS analysis compare to previous research.

The result for the total material stock in Hamburg's buildings, obtained from this GIS bottom-stock analysis, is generally comparable. It accounts for 82% of the value determined by Haberl et al. (2021) and is situated in the larger third of the range given by Schiller et al. (2010). The determined per capita value for material in the residential building stock is 17.2% smaller than the one given by IÖR (2022). This is a similar deviation as for the first comparison made. Looking at previously determined values for the stock in total urban buildings per capita of Berlin and Vienna (Haberl et al., 2021; Kleemann et al., 2017; Lederer et al., 2021), the result of this research is comparable, except for the value determined by Kleemann et al. (2017), which also stands out in comparison to the other two studies. It is impossible to judge which research yields better or more exact results, as

Table 5.1: Comparison of materials stock results with prior research.

	This study	Prior research	Source	Comment
Total material stock for Hamburg	0.280 Gt	0.341 Gt	(Haberl et al., 2021)	Source: Values given per federal state in Germany. Study uses satellite data, OSM data and MI (bottom-up)
		0.080 - 0.396 Gt	(Schiller et al., 2010)	Source: Value derived from statistical data (top-down)
Material per area	371,086 t/km^2	220,000 - 1,300,000 t/km^2	(Peled & Fishman, 2021)	Source: Range given per county in Germany This study: Calculating with an area of 755.09 km^2 for Hamburg
Material per capita (residential buildings)	76.19 t/capita	92 t/capita	(IÖR, 2022)	Source: Value given for the federal state of Hamburg This study: Calculating with the population in 2018 = 1,841,179 people
Stock in total urban buildings per capita	152.13 t/capita	ca. 170 t/capita	(Haberl et al., 2021)	Source: Total value given for Berlin, divided by the population for comparison This study: Total material stock divided by population
		ca. 150 t/capita	(Haberl et al., 2021)	Source: Value per capita given for Vienna
		210 t/capita	(Kleemann et al., 2017)	Source: Value per capita given for Vienna
		156 t/capita	(Lederer et al., 2021)	Source: Total value given for Vienna, divided by population for comparison

the true material contents of buildings cannot be determined before their demolition. However, the more data points are available, the easier it is to identify whether results are generally within the same magnitude. The latter is true for this analysis' results, especially in the urban context, which validates the values as suitable new points of comparison for future research.

The analysis of the distribution of the nine materials studied in Hamburg's buildings shows that the stock consists mainly of concrete and other mineral materials. Together they make up 85% of the stock. This implies that stakeholders involved in the demolition of buildings in Hamburg can generally expect to find these two materials in bulk.

Comparing the shares displayed in Figure 4.6 with findings from studies on the national level validates the findings of this study. Bigalke et al. (2015) state that 12.7% of buildings in Germany have a non-residential function, which matches with the share for Hamburg (13%) in this research. Furthermore, Ortlepp and Schiller (2015) estimate the total floor area for residential and non-residential buildings with shares of 54.34% and 45.66%, respectively, similar to the 59% to 40% ratio in this study. Lastly, they calculate the total material mass in Germany's building stock to be distributed by 44.37% in non-residential buildings and 55.63% in residential buildings. This is also in line with the values found in this study of 49% for non-residential buildings and 50% for residential buildings.

These ratios show that non-residential buildings are few in number, but large in size and quantity of material, meaning they contain more material in a single object than buildings of other functions. This makes them especially interesting in a UM context, as large amounts of materials could be mined in a small and specific location. In contrast, garages are less interesting in a UM context, as individual objects contain small amounts of materials and are scattered in space.

A strength of this study is the obtained information on material quantities in non-residential buildings. Due to the available data on exact building functions, non-residential buildings are better differentiated in their unique characteristics and office, trade and warehouse buildings are identified as holding the largest material stock within this function group. Contributing half of the materials to the total building stock of Hamburg, their properties should continue to be explored.

Regarding residential buildings, those built in the post-war cohort of *1949-1978*, stand out in this analysis, as MFHs from this period account for the largest mass of concrete, other minerals and brick found in a single MI class. In comparison with SFH, the number of MFHs in this cohort is smaller, implying that MFHs built between 1949 and 1978 are material hotspots within Hamburg's building stock.

Looking at the spatial distribution of materials in Hamburg, densely built-up and industrial areas exhibit high material density. Furthermore, material density is high in an area of a half-circle pattern around the city centre. Looking at the location of different residential building types, this is an area where MFHs prevail. Simultaneously, material density is low in the outer 'ring' of the city, which correlates with the location of areas where SFH dominate. The spatial distribution of materials in the areas characterised by agricultural use in the southwest and southeast is interesting to see and presents a unique property to a large city such as Hamburg. The described spatial distribution makes industrial areas and areas with predominantly MFHs especially interesting in an UM context, as large amounts of materials are concentrated in these locations.

MFA Model

The results of the model show high renovation activity for the most recent cohort. Demolition activity is highest for the buildings built between 1949 and 1978, exhibiting the highest share of demolition across the entire studied time frame. As mentioned before, it is also the cohort where residential buildings contain a large amount of materials. This, again underlines the required focus on buildings from the post-war period. Ideally, renovation rates should be increased to prevent demolition and maintain materials in buildings, avoiding material losses in quality and quantity due to recycling. If demolition is not avoidable, demolition and recycling concepts could ensure a high recycling share for the material outflows. This is something that specifically needs to be explored by policymakers and politicians in Hamburg, as the introduction of policies could control the dynamics of renovation and demolition activities.

Regarding material in- and outflows, the predicted values have to be set into context. While clear differences in the flows can be seen - sometimes from one year to the next - the author emphasises that they are still uncertain prospective values and do not represent that material flows are exactly determined for every year. Still, the results underline the impact of demolition, which causes significantly larger material outflows - and inflows - than renovation measures. While Wiedenhofer et al. (2015) do not calculate the outflows of materials from renovation activity, they find the material demand for renovation to be higher than for replacement construction, which is not true to the results of this research. As replacement construction is triggered by demolition activity, the cause for the disparity in these results can be attributed to the demolition rates inherent to the studies. Wiedenhofer et al. (2015) assume a demolition rate of 0.15%, while the lifetime modelling approach of this research results in demolition rates of approximately 0.3% around 2020, 0.55% in 2050 and 0.75% in 2075. The latter value, however, matches with the demolition rate of 0.7%, determined for the city of Leiden until 2030 by Verhagen et al. (2021). Although it is not possible to identify the cause for the difference and similarity of this research's demolition rate to the literature, the author suggests that demolition rates could be higher in cities - such as Leiden and Hamburg. Further research into lifetime modelling, especially considering local characteristics, could give an answer to this question.

Based on the characteristics of the individual buildings in Hamburg's stock, this study determines the renovation at approximately 2.3% in 2020 and 2.6% in 2035 before it almost stabilises around 2.2% after 2060. This information is relevant to the City of Hamburg, as it displays the renovation needs intrinsic to the buildings' characteristics. The values can be used to benchmark current renovation activity against the required one.

Secondary Material

The obtained results for secondary material supply have to be understood as rough estimations, giving a first impression of whether secondary materials from demolition and renovation activities could cover the demands resulting from renovation and replacement construction. As mentioned in Section 2.6, recycling processes for different material types and qualities in construction are highly complex and depicting a detailed and complete picture of this topic is outside the scope of this research.

At least for brick, secondary materials show the potential to cover demand. Due to changing building stock composition, the outflow of bricks is higher than the inflow. This result is especially relevant to EOL operators in Hamburg. If they ensure the recycling of the brick outflows, ideally at high quality, the saturation potential of material demand through secondary materials could be unlocked. However, brick is regarded as a labour-intensive material, introducing uncertainties to its future usage in construction due to skilled labour shortages. Considerations regarding the future use of materials in construction might also be relevant for other materials. Yet, this debate is outside the scope of this study.

For all other materials, a partial substitution of primary with secondary material can be achieved. As this research does not go into the detailed recycling characteristics of materials and feasible shares of recycled content within construction materials such as concrete, no exact shares of expected primary material substitution are given. However, the study makes a first evaluation of the general secondary material generation potential in the context of Hamburg. To achieve more robust results, this calculation requires validation, specifically on the part of assumed recycling shares. As initially mentioned in this report, Hamburg does not have clear policy goals for reducing primary material consumption in construction. The determined potential of secondary material can thus serve as a basis for policymakers to start discussing feasible goals.

Spatio-Temporal Aspects

The location of buildings to be demolished until 2030 is found to be more or less equally distributed across the city. Only the wider city centre shows a higher density of buildings predicted to be demolished by 2030. This spatial distribution has to be analysed by experts of EOL operators, however, the author highlights that transport distances should be kept as small as possible. This suggests locating multiple collection and treatment facilities for CDW with smaller capacity in the outer areas of the city and a few facilities with higher capacity close to the city centre. The latter could prove to be difficult, as competition for space is high in urban centres. If certain collection and treatment facilities for CDW could only treat specific materials, they could also be mapped out depending on this factor. This research has information available on the distribution of single materials in the stock, as for example shown in Figure S.1, Appendix S. A comparison of brick and concrete distribution within Hamburg shows that high brick density is present in a more spread-out pattern, while concrete density is specifically high in the city centre and locations pointed out in 4.9. At least from a spatial perspective, these findings inform EOL operators and potentially support strategic planning for EOL facilities.

Considering the temporal aspect of material outflows and inflows within this research, inflows are predicted to be shifted in time, peaking with a one-year delay to outflows. Although this result encompasses limitations introduced by modelling choices, which will be discussed in the section below, it would hold true for constant maintenance of the building stock. The described time lag implies that storage locations are required in the city, where secondary materials recovered from the outflows can be stored until they are in demand again. This again could prove to be difficult due to the competition for space in urban centres.

5.2. Discussion of the Methods

Material Intensities

This study is bound to the available material intensities of IÖR (2023), as these are the most developed ones available in the German context. The present study reveals three main limitations inherent to these values: 1) The MI values for non-residential buildings do not differentiate between different age cohorts, meaning that for example a building built in 1850 is modelled with the same materials as a building built in 2010. This is problematic for materials like plastics, which only became a common construction material around the 1950s. For a general stock model, this is not necessarily a false assumption as the material intensities can be understood as averages across non-residential buildings when looking at the total stock. On the level of individual buildings that have information on the exact construction year, however, it distorts the spatial distribution of materials. As the stock data is also used as an input to the dynamic MFA model this issue introduces slight uncertainties to the calculated outflows. However, this distortion will be minimal as non-residential buildings built before 1950 only contain 7.8% of all plastic in the stock, while non-residential buildings in total make up for approximately 45% of plastics in the stock. 2) For residential buildings, IÖR (2023) only provides one MI for buildings since 1990. However, new building types were developed in the last two decades, e.g. low-energy buildings, which emerged around the year 2000 and since then became more common. The representation of specifically insulation materials or glass in the MI class after 1990 might therefore not be accurate for recently built buildings. I thus recommend to extend the database of (IÖR, 2023) to include MI values for more recent age cohorts. 3) For all MI classes, the applied MIs do not consider changes in material composition due to renovation activities, that took place in the time from construction until today. Another study (Haberl et al., 2021) applying the same MI values does not mention this issue, thus, it is assumed that results stay comparable with this research, where such renovation activities are not considered. This implies, however, that the current stock might be larger than determined by this and other research.

In comparison to other studies (Haberl et al., 2021; Heinrich, 2019; Kleemann et al., 2017; Verhagen et al., 2021), this research considers a rich and varied set of MIs, already due to the fact that it explores not only residential but also non-residential buildings. Even in comparison to stock accounting research on non-residential buildings in a German context (Ortlepp et al., 2016; Ortlepp et al., 2015; Schebek et al., 2017) this study could further differentiate within the non-residential building function, as IÖR (2023) updated the MI values to specify nine different types. Although this is a detailed categorisation, the original data on the specific functions of non-residential buildings in Hamburg is significantly more detailed, meaning the potential of the information depth could not fully be unlocked. Similarly, the data on different types of residential buildings could be further distinguished as done for example by Verhagen et al. (2021), considering row houses and high-rise buildings, accounting for specifics such as the former sharing at least one outer wall and thus being less material intensive. The GIS data acquired within this research includes attributes for making such a distinction, allowing for an update of categorisation if the MIs of IÖR (2023) were to be further developed.

In relation to the categorisation of residential buildings this study came across the following issues: Classifying buildings with a residential function as either SFH or MFH presented a challenge in the German context. In other contexts, such as The Netherlands, this classification is often performed by looking at the number of addresses per building. However, in Germany, different units within the same building share one address, which is connected to the building as a whole. Therefore, an approach unique to this research was developed, introducing uncertainties to this research. Moreover, this challenge raises the question, of whether it is even reasonable to differentiate between SFH and MFH. Within this categorisation, it remains unclear where to sort buildings with mixed-use functions. Besides, large SFHs, especially in the luxury segment often house one family, but the properties and measurements are still similar to an MFH. To conclude, this categorisation is to be questioned. Nevertheless, the developed stock model can easily be adapted for example to be used with MI values based on the construction type of buildings (concrete, masonry, etc.). The dataset used in this analysis, however, does not contain any information on the construction type of buildings, which is why such an approach would require assumptions to be made for the proportions of respective building types in the building stock. Such an analysis could serve as an interesting point of comparison to the stock values determined by applying the MI of IÖR (2023).

Furthermore, the choice of using MIs based on the m^2 of GFA is to be discussed. While this unit of measurement matches better with the available data, some issues indicate that using MIs per building volume (m^3) could be more reliable. First of all, the comparison of height data with the available data on the number of floors shows that deriving data on the latter from 3D models is subject to major uncertainties. If 3D models are available, the choice of MIs based on the building volume is preferable. The author expects that this combination will also depict reality more accurately and precisely, as it takes into account height differences within a building, at least for 3D models with a minimal LoD of 2.

Lastly, it should be mentioned that the MIs are based on representative building types found across Germany, while there are significant differences in construction methods between, for example, southern and northern Germany. This issue is also raised by Heeren and Hellweg (2019) in the context of their study in Switzerland. However, capturing such differences would require an extreme level of detail and it is unclear at this point whether the benefits would outweigh the effort. To a certain extent, this research accounts for local specifics. For one, the prevailing garage construction types are explored using Google Street View, as described in Section 3.1, respecting some local characteristics for this MI category. Furthermore, local features also influence the sorting decisions made for SFH and MFH, as described in Subsection 3.2.4.

Construction Year Allocation

The data reliability for the construction year data leads to a limitation of this research. Although I verify the data with real estate advertisements, this research cannot judge the reliability of this platform. Since the construction year allocation yields results similar to statistical records, the data is understood to be reliable in its distribution of years. However, this does not necessarily correlate with the data being spatially accurate. Ideally, the acquired datasets will be updated soon, providing a possibility to validate this research's results.

Filling the data gaps of construction years with the described allocation method proves to be a reliable tool, as results are similar to data recorded in statistics. Limitations of this approach include the overall still quite experimental design. I base buffer choices on visual checks, but more testing would improve the determination of ideal sizes. Choosing bigger buffers could give a more complete picture of the surroundings of a building, but also carries the risk of concealing data from neighbouring buildings. The study of (Heeren & Hellweg, 2019) face a comparable challenge in closing a data gap for construction years as only 45% of objects contain this attribute data, similar to the 42.2% completeness in this research. They allocate construction years from an empirical distribution. Wherever this is not possible, they choose to allocate construction year data from buildings with similar characteristics in a 300m radius. This approach gives an interesting opportunity for future exploration by comparing the approach of this research with the one by Heeren and Hellweg (2019). Future research could also employ machine learning to detect similarities in the size or shape of nearby buildings, although it has to be discussed whether this method would be too costly and time-consuming for the actual outcome. Another important limitation specific to how I perform allocation in the scope of this research is that whenever multiple construction years with the same occurrence are available for allocation, the largest one is allocated. This is due to the nature of the employed tool in ArcGIS and could be an explanation for the slight overestimation of the most recent age cohort, as it was already well-documented before allocation. Furthermore, I emphasise that due to the utilization of the dataset on monumental buildings many old building years are known, especially in the city centre. This has an influence on the way construction years are allocated in this area and introduces uncertainties.

In a comparative analysis, this study reflects upon the construction year allocation and its impact on the results for the total material stock in residential buildings. Non-residential buildings and garages are excluded, as the age of these buildings does not influence their material content in this research. Figure M.1 in Appendix M visualises the obtained material stock results based on the performed allocation next to two scenarios, where I fill data gaps in construction years by assigning the newest and oldest age cohort, respectively. Interestingly, the total sum of materials is almost the same for all three cases. Filling the data gaps with either the oldest or the most recent age cohort produces almost identical values for the total stock of residential buildings, namely 2% and 0.3% lower than the detailed allocation method. The share of individual materials in the total mass does not change much either. A slight difference occurs for brick, with a higher share when assigning the oldest cohort and a smaller one when assigning the newest cohort. For the performed construction year allocation the share of bricks approximately reaches a value in between the two. For the sole purpose of calculating the absolute mass for different materials in the stock, the allocation's necessity can be questioned. Nevertheless, the construction year allocation makes it possible to achieve a complete dataset required as input to the MFA model.

GIS Stock Analysis

Overall, this GIS-based stock analysis proved that bottom-up studies can employ available cadastre data despite the occurrence of gaps in the attribute data and produce results comparable to prior research. The performed stock analysis can therefore serve as a basis for detailed urban resource cadastres, such as the studies of Kleemann et al. (2017) and Lanau and Liu (2020). Considering the possibilities of remote sensing tools for stock accounting, the approach of Haberl et al. (2021) would yield too coarse results for such a cadastre. However, remote sensing also includes the generation of LiDAR data, often the base of urban 3D models. As such, remote sensing could also contribute to the urban context, generating 3D building models, which - combined with MI per m^3 of gross volume - present an alternative approach to quantifying the material stocks of individual buildings. The author expects this approach to be strong in depicting the true size of buildings, including roof shapes or different heights within a building and thus, representing reality better than approaches based on floor space.

MFA Model

By setting the scope of the MFA model to only include building stock maintenance a limitation is introduced to the MFA model. It is unusual for MFA studies to ignore the extension of the stock, as studies usually include new construction (Bergsdal et al., 2007; Heeren & Hellweg, 2019; Heinrich, 2019; Ortlepp et al., 2018; Wiedenhofer et al., 2015). However, Hamburg's population is projected to almost develop towards stagnation in the middle of this century, as described in Section 1.1. This is a reasonable argument to neglect residential stock extension within the scope of this research. The influence of population development in non-residential buildings is unknown but can be argued to have similar effects as for residential buildings. In any case, looking solely at stock maintenance still allows for drawing conclusions on future in- and outflows of materials and secondary material supply. If the latter cannot cover material demand for stock maintenance, it is not expected to cover material demand for stock extension, at least in the short term.

This research applies a unique approach of not only calculating the material stocks on the building level but also determining future in- and outflows of materials per individual building in a dynamic manner. So far, studies acquiring building-level data on material stocks usually aggregate the results either by floor space per year (Heinrich, 2019), grid cells (Han et al., 2018) or regions (Heeren & Hellweg, 2019). Other studies working with granular GIS-based data either perform static MFA studies (Verhagen et al., 2021) or employ the combination of methods in the retrospective (Han et al., 2018; Miatto et al., 2019). Thus, the methodological approach of this research is novel in maintaining its granular resolution in prospective dMFA. It is not possible to identify if one of these approaches is better than others but this study serves as a useful proxy to explore whether the increased effort of granular modelling leads to relevant results not obtainable by other approaches.

Material flows in this research can only be determined from 2019 onwards, as the model assumes a one-year time lag between demolition and replacement construction. The choice to model the lifetime of buildings solely based on their age introduces a modelling limitation, as the model neglects external influences such as urban planning measures. While some researchers claim the latter to have more influence on a building's lifetime than the building's age properties (Kohler & Yang, 2007), this research argues that lifetime parameters in literature are often derived from real-world observations, meaning external factors are included in observed lifetimes. In general, data on the lifetime of buildings with different functions is scarce, as pointed out by other researchers (Heeren & Hellweg, 2019; Miatto et al., 2017). Considering the just mentioned influential factors on building lifetime, a high regional specificity is detected, suggesting research on building lifetime is generally hindered by its limited transferability to other contexts.

This study assigns individual lifetimes to buildings, an approach also used by Heeren and Hellweg (2019). In contrast to Heinrich (2019), who applies a general standard deviation for the lifetime of all individual buildings, this study models lifetime in more detail, by applying a truncation to the Weibull distribution and introducing longer lifetimes to older buildings in the stock. This approach is strong in modelling lifetimes closer to real-world data, as constant parameters are a simplification found to have the potential of introducing error to results (E. Müller et al., 2014). They neglect the fact that stocks include buildings from different age cohorts displaying unique characteristics. However, retrospective GIS analyses would improve the accuracy of assumed average lifetimes significantly. In their research, Miatto et al. (2019) showcase that lifetimes change greatly for the different age cohorts in the stock of Padua, Italy. The disparity of modelled lifetimes and real-world demolition rates is also emphasised by Wiedenhofer et al. (2015), who state that demolition in the European context is mostly overestimated. In relation to lifetime modelling, the unknown accuracy of the construction years for non-residential buildings has to be noted as a limitation caused by the input data. The distribution of construction years for this function group is skewed towards the most recent age cohort, meaning outflows from this cohort could be underestimated for the first part of the model.

Overall it should be noted that the lack of standardisation in the application of GIS and MFA generally introduces uncertainties, but this holds true for all research utilising these tools. Still, standardisation efforts in this area of research should be discussed.

6

Conclusion and Recommendations

This research employs a unique approach of combining a GIS-based bottom-up stock analysis with a prospective dMFA on the level of individual buildings in the stock of Hamburg, Germany. The scope of the stock is set to include residential buildings, non-residential buildings and garages. The developed model and specifically its granularity allow for modelling lifetime scenarios, renovation activities, changes in material composition etc. on the micro-scale of individual buildings. This way, the impact of specific policies can for example be modelled for certain age cohorts and function types in the stock or only for a spatially defined area within the city. This research furthermore showcases the possibilities of using openly available cadastre data for building stock studies and explores the challenges inherent in this approach.

The study´s results answer the main research question as follows: The material required for maintaining Hamburg's building stock in its current state by renovating and replacing demolished buildings cannot be fully satisfied by secondary material sourced from outflows of renovation and demolition. Brick represents an exception, as outflows are predicted to be significantly higher than inflows. After deducting recycling losses from the brick outflows, the determined secondary material supply still yields higher values than the predicted demand. The study draws the conclusion that it is difficult to quantify the future self-sufficiency level, as this requires immensely deep knowledge about material properties and feasible shares of recycling content in construction material, which are topics to be explored outside the scope of this research. However, the obtained results are good enough to act as a first exploration of the general dynamics of Hamburg's building stock, building a solid foundation for future analysis and generating relevant recommendations.

The recommendations for stakeholders in Hamburg and other researchers derived from this research are already discussed in Chapter 5. Still, an overview is summarised here:

- The city's/municipality's institutions:
  - Update cadastre information / spatial data to verify and improve results before they are ultimately communicated to the other stakeholders.
  - Launch research projects to further analyse residential buildings from the post-war cohorts, as they need to be the focal point of building preservation in the next decades.
- EOL operators:
  - Prepare for high-quality brick recycling to unlock the saturation potential of material demand through secondary materials.
  - Review current waste treatment capacities with regard to predicted outflows, especially for bulk materials such as concrete and other minerals, that account for 85% in Hamburg's building stock.
  - Expert knowledge is required to find suitable locations for recycling facilities in the city in relation to the spatial distribution of outflows from demolition.
  - Taking into account the determined material outflows and the future demand, storage concepts are required to maximise secondary material potential.
- Politicians and policymakers:
  - Start the discussion on potential goals for the reduction of primary material consumption in construction in Hamburg.
  - Explore the possibility of introducing policies motivating renovation and avoiding demolition.
- Urban planners, architects, engineers:
  - Explore the application of the developed stock accounting and MFA model in a practical context to quantify impacts of e.g. renovation measures, possibly on a refined level such as a neighbourhood.
- IE researchers:
  - The developed methodology contributes to the methodologies of IE and can be adapted and applied in the context of other local-level research.

Future Research

Future research could include infrastructure stocks in the MFA analysis and connect recycling pathways of e.g. concrete, which is often downcycled in road construction. With increased high-quality recycling of concrete trade-offs could arise for materials required in infrastructure construction.

Including both stocks, buildings and infrastructure, such trade-offs could be modelled beforehand. Furthermore, this MFA study could be enriched by connecting material quantities with environmental impacts (e.g. emissions). Quantifying material consumption is only a small part of the bigger picture as the mass of a specific material and its environmental impact do not necessarily correlate. This is especially true for lightweight fossil-based materials such as insulation.

In relation to urban planning strategies and the mobility transition, the findings on garages could be used for further research. Specifically larger garages of MFH could be considered for repurposing measures. During this research, it remained partially unclear how basements and mezzanine floors are represented in available MIs. This could be a future object of study.

Another possibility would be the introduction of agent-based modelling (ABM) to this field of research. ABM is a powerful tool to model interactions between agents and objects over space and time. This could be especially helpful in testing the effectiveness and impact of recycling strategies and policies in a modelling environment before putting them into practice, thereby identifying potential trade-offs and problematic links in the system. Especially in a sector where the network of stakeholders is so complex, a versatile tool like ABM could generate informative new insights.

In the face of climate change and rising sea levels, Hamburg´s risk of flooding is also increasing. As knowledge of the spatial distribution of materials was used in disaster analysis before (Tanikawa et al., 2015), the model's ability to assess the amount and location of stocks at risk should be tested.

Reflection

One of the biggest challenges in this research was the lack of transparency in scientific papers. Many times, exact values used as inputs to models were neither stated in the paper nor the SI. Understandably, detailed documentation is challenging for large models. Still, the lack of transparency hinders the reproducibility of research and data accessibility for projects dependent on already available data, such as this master thesis. One example are the applied material intensities, which are part of an open-access database. Despite being easily accessible, they lack essential background information, which is only available in a report that has to be ordered as a hard copy. Furthermore, the MIs are often modified for research, but not all papers document the process of recalculation transparently. Consequently, it is hard to know whether the results obtained with these MIs are even comparable across different studies. Of course, there are examples of good research, where all input parameters are carefully documented. This work aims to be such an example and a reminder to keep research transparent and reproducible at any time.

References

Adams, K. T., Osmani, M., Thorpe, T., & Thornback, J. (2017). Circular economy in construction: Current awareness, challenges and enablers [Publisher: ICE Publishing]. *Proceedings of Institution of Civil Engineers: Waste and Resource Management*, *170*(1), 15–24. https://doi.org/10.1680/jwarm.16.00011

AdV. (2018). *ALKIS-Objektartenkatalog DLKM. Dokumentation zur Modellierung der Geoinformation des amtlichen Vermessungswesens.* (Version 7.1 rc.1). Arbeitsgemeinschaft der Vermessungsverwaltungen der Länder der Bundesrepublik Deutschland (AdV).

Augiseau, V., & Barles, S. (2017). Studying construction materials flows and stock: A review. *Resources, Conservation and Recycling*, *123*, 153–164. https://doi.org/10.1016/j.resconrec.2016.09.002

Baumann, M. A., Jim. (2009). What Is The Geographic Approach? | Fall 2009 | ArcNews. Retrieved October 15, 2023, from https://www.esri.com/about/newsroom/arcnews/what-is-the-geographic-approach/

Bergsdal, H., Brattebø, H., Bohne, R. A., & Müller, D. B. (2007). Dynamic material flow analysis for Norway's dwelling stock. *Building Research & Information*, *35*(5), 557–570. https://doi.org/10.1080/09613210701287588

Bigalke, U., Zhang, Y., Kunde, J., Schmitt, M., Zeng, Y., Discher, H., Bensmann, K., & Stolte, C. (2015). *Der dena-Gebäudereport 2015. Statistiken und Analysen zur Energieeffizienz im Gebäudebestand.* Deutsche Energie-Agentur GmbH (dena).

Bründlinger, T., Marcinek, H., Stahl, C., & Stolte, C. (2021). *Fokusthemen zum Klimaschutz im Gebäudebereicht. dena-Gebäudereport 2021.* Deutsche Energie-Agentur GmbH (dena).

Demografie Portal. (2023). Demografieportal - Fakten - Bevölkerungszahl in Hamburg. Retrieved November 16, 2023, from https://www.demografie-portal.de/DE/Fakten/bevoelkerungszahl-hamburg.html

Di Maria, A., Eyckmans, J., & Van Acker, K. (2018). Downcycling versus recycling of construction and demolition waste: Combining LCA and LCC to support sustainable policy making. *Waste Management*, *75*, 3–21. https://doi.org/10.1016/j.wasman.2018.01.028

Esri. (2023a). Climate Action Solutions | Adaptation & Resilience with Location-Based Risk Analytics. Retrieved November 23, 2023, from https://www.esri.com/en-us/about/climate-action/overview

Esri. (2023b). What is GIS? | Geographic Information System Mapping Technology. Retrieved October 26, 2023, from https://www.esri.com/en-us/what-is-gis/overview

Gallego-Schmid, A., Chen, H. M., Sharmina, M., & Mendoza, J. M. F. (2020). Links between circular economy and climate change mitigation in the built environment [Publisher: Elsevier Ltd]. *Journal of Cleaner Production*, *260*. https://doi.org/10.1016/j.jclepro.2020.121115

Google Maps. (2023). Google Street View. Retrieved November 15, 2023, from https://www.google.de/maps/

Göswein, V., Silvestre, J. D., Habert, G., & Freire, F. (2019). Dynamic Assessment of Construction Materials in Urban Building Stocks: A Critical Review [Publisher: American Chemical Society]. *Environmental Science & Technology*, *53*(17), 9992–10006. https://doi.org/10.1021/acs.est.9b01952

Gruhler, K., & Böhm, R. (2011). *Auswirkungen des demografischen Wandels auf das Stofflager und die Stoffflüsse des Wohngebäudebestandes-Deutschland 2050* (Band 25). Fraunhofer IRB-Verlag.

Gruhler, K., & Deilmann, C. (2015). *Materialaufwand von Nichtwohngebäuden. Verfahrensschritte zur Abbildung der Ressourceninanspruchnahme des Nichtwohnbau-Bestandes.* (Band 45). Fraunhofer IRB-Verlag.

Gruhler, K., & Deilmann, C. (2017). *Materialaufwand von Nichtwohngebäuden - Teil II.* (Band 48). Fraunhofer IRB-Verlag.

Gülck, K. H. (2022). Kreislauffähige Konzepte im Bauwesen – Gebäude als Materialdepots. In T. Kölzer (Ed.), *Nachhaltige und digitale Baukonzepte: Methoden und Wege zu einer ökologisch ausgerichteten Baubranche* (pp. 37–58). Springer Fachmedien. https://doi.org/10.1007/978-3-658-36776-3_2

Haberl, H., Wiedenhofer, D., Schug, F., Frantz, D., Virag, D., Plutzar, C., Gruhler, K., Lederer, J., Schiller, G., Fishman, T., Lanau, M., Gattringer, A., Kemper, T., Liu, G., Tanikawa, H., Van Der Linden, S., & Hostert, P. (2021). High-Resolution Maps of Material Stocks in Buildings and Infrastructures in Austria and Germany [Publisher: American Chemical Society]. *Environmental Science and Technology*, *55*(5), 3368–3379. https://doi.org/10.1021/acs.est.0c05642

Han, J., Chen, W.-Q., Zhang, L., & Liu, G. (2018). Uncovering the Spatiotemporal Dynamics of Urban Infrastructure Development: A High Spatial Resolution Material Stock and Flow Analysis [Publisher: American Chemical Society]. *Environmental Science & Technology*, *52*(21), 12122–12132. https://doi.org/10.1021/acs.est.8b03111

Heeren, N., & Hellweg, S. (2019). Tracking Construction Material over Space and Time: Prospective and Geo-referenced Modeling of Building Stocks and Construction Material Flows [_eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/jiec.12739]. *Journal of Industrial Ecology*, *23*(1), 253–267. https://doi.org/10.1111/jiec.12739

Heeren, N., Mutel, C. L., Steubing, B., Ostermeyer, Y., Wallbaum, H., & Hellweg, S. (2015). Environmental Impact of Buildings—What Matters? [Publisher: American Chemical Society]. *Environmental Science & Technology*, *49*(16), 9832–9841. https://doi.org/10.1021/acs.est.5b01735

Heinrich, M. A., & Lang, W. (2019). Capture and Control of Material Flows and Stocks in Urban Residential Buildings [Issue: 1 ISSN: 17551315]. *IOP Conference Series: Earth and Environmental Science*, *225*. https://doi.org/10.1088/1755-1315/225/1/012001

Heinrich, M. A. (2019). *Erfassung und Steuerung von Stoffströmen im urbanen Wohnungsbau - Am Beispiel der Wohnungswirtschaft in München-Freiham*.

Hien, H. M., Trung, T. N., Looijen, W., & Hulsbergen, K. (2005). Flood Vulnerability Analysis and Mapping in Vietnam. In P. van Oosterom, S. Zlatanova, & E. M. Fendel (Eds.), *Geo-information for Disaster Management* (pp. 67–83). Springer. Retrieved November 23, 2023, from https://doi.org/10.1007/3-540-27468-5_6

ImmoScout24. (2023). ImmoScout24 – Die Nr. 1 für Immobilien. Retrieved November 24, 2023, from https://www.immobilienscout24.de/?seaid=g_brand&gad_source=1&gclid=CjwKCAiAjfyqBhAsEiwA-UdzJL9LCUqybfLW7ixjOxCGJzpFmjvTPcmQJEH9Rmq5IeCNEM2LnvRI4BoCzYMQAvD_BwE

immowelt. (2023). Immobilien - Häuser - Wohnungen - finden bei immowelt.de. Retrieved November 24, 2023, from https://www.immowelt.de

IÖR. (2022). IÖR Monitor. Retrieved October 19, 2023, from https://www.ioer-monitor.de/

IÖR. (2023). Informationssystem Gebaute Umwelt des Leibniz-Institut für ökologische Raumentwicklung e.V. Retrieved October 19, 2023, from https://ioer-isbe.de/

Jenis, K. (2023). *Material stock of buildings in Brno. Towards circularity in the construction and demolition industry* (Master's thesis). Leiden University and Delft University of Technology. https://repository.tudelft.nl/islandora/object/uuid%3A6d8ab50e-685f-4473-b77a-a6253e0f57a1?collection=education

Kaufman, S. M. (2012). 3 - Quantifying sustainability: Industrial ecology, materials flow and life cycle analysis. In F. Zeman (Ed.), *Metropolitan Sustainability* (pp. 40–54). Woodhead Publishing. https://doi.org/10.1533/9780857096463.1.40

Kleemann, F., Lederer, J., Rechberger, H., & Fellner, J. (2017). GIS-based Analysis of Vienna's Material Stock in Buildings [Publisher: Blackwell Publishing]. *Journal of Industrial Ecology*, *21*(2), 368–380. https://doi.org/10.1111/jiec.12446

Kohler, N., & Yang, W. (2007). Long-term management of building stocks. *Building Research & Information*, *35*(4), 351–362. https://doi.org/10.1080/09613210701308962

Kühlen, A. (2016). *State of the Art of Demolition and Reuse and Recycling of Construction Materials*.

Lanau, M., & Liu, G. (2020). Developing an Urban Resource Cadaster for Circular Economy: A Case of Odense, Denmark [Publisher: American Chemical Society]. *Environmental Science & Technology*, *54*(7), 4675–4685. https://doi.org/10.1021/acs.est.9b07749

Landesbetrieb Geoinformation und Vermessung. (2023). Geoportal Hamburg. Retrieved November 15, 2023, from https://geoportal-hamburg.de/geo-online/

Lederer, J., Fellner, J., Gassner, A., Gruhler, K., & Schiller, G. (2021). Determining the material intensities of buildings selected by random sampling: A case study from Vienna. *Journal of Industrial Ecology*, *25*(4), 848–863. https://doi.org/10.1111/jiec.13100

Miatto, A., Schandl, H., Forlin, L., Ronzani, F., Borin, P., Giordano, A., & Tanikawa, H. (2019). A spatial analysis of material stock accumulation and demolition waste potential of buildings: A case study of Padua [Publisher: Elsevier B.V.]. *Resources, Conservation and Recycling*, *142*, 245–256. https://doi.org/10.1016/j.resconrec.2018.12.011

Miatto, A., Schandl, H., & Tanikawa, H. (2017). How important are realistic building lifespan assumptions for material stock and demolition waste accounts? [Publisher: Elsevier B.V.]. *Resources, Conservation and Recycling*, *122*, 143–154. https://doi.org/10.1016/j.resconrec.2017.01.015

Müller, D. (2006). Stock dynamics for forecasting material flows—Case study for housing in The Netherlands. *Ecological Economics*, *59*(1), 142–156. https://doi.org/10.1016/j.ecolecon.2005.09.025

Müller, E., Hilty, L. M., Widmer, R., Schluep, M., & Faulstich, M. (2014). Modeling Metal Stocks and Flows: A Review of Dynamic Material Flow Analysis Methods. *Environmental Science & Technology*, *48*(4), 2102–2113. https://doi.org/10.1021/es403506a

Ortlepp, R., Gruhler, K., & Schiller, G. (2016). Material stocks in Germany's non-domestic buildings: A new quantification method. *Building Research and Information*, *44*(8), 840–862. https://doi.org/10.1080/09613218.2016.1112096

Ortlepp, R., Gruhler, K., & Schiller, G. (2018). Materials in Germany's domestic building stock: Calculation model and uncertainties [Publisher: Routledge]. *Building Research and Information*, *46*(2), 164–178. https://doi.org/10.1080/09613218.2016.1264121

Ortlepp, R., Gruhler, K., Schiller, G., & Ortlepp, S. (2017). Grundlagen für materialeffizientes Planen und Bauen: Baustoffzusammensetzung des deutschen Nichtwohngebäudebestands. *Bautechnik*, *94*(1), 10–18. https://doi.org/10.1002/bate.201600022

Ortlepp, R., & Schiller, G. (2015). *Mineral building material stock of buildings and infrastructures in Germany and flows as indicators for recycling potentials*. High Performance Fiber Reinforced Cement Composites (HPFRCC7). Stuttgart.

Ortlepp, R., Schiller, G., Deilmann, C., & Gruhler, K. (2015). The other "half of the city"-analysis of non-residential building stock and its materials. *SASBE 2015 Proceedings*, 271–280.

Pauliuk, S., & Heeren, N. (2021). Material efficiency and its contribution to climate change mitigation in Germany: A deep decarbonization scenario analysis until 2060 [Publisher: Blackwell Publishing]. *Journal of Industrial Ecology*, *25*(2), 479–493. https://doi.org/10.1111/jiec.13091

Peled, Y., & Fishman, T. (2021). Estimation and mapping of the material stocks of buildings of Europe: A novel nighttime lights-based approach. *Resources, Conservation and Recycling*, *169*, 105509. https://doi.org/10.1016/j.resconrec.2021.105509

Sandberg, N. H., Sartori, I., Heidrich, O., Dawson, R., Dascalaki, E., Dimitriou, S., Vimm-r, T., Filippidou, F., Stegnar, G., Šijanec Zavrl, M., & Brattebø, H. (2016). Dynamic building stock modelling: Application to 11 European countries to support the energy efficiency and retrofit ambitions of the EU. *Energy and Buildings*, *132*, 26–38. https://doi.org/10.1016/j.enbuild.2016.05.100

Sartori, I., Bergsdal, H., Müller, D. B., & Brattebø, H. (2008). Towards modelling of construction, renovation and demolition activities: Norway's dwelling stock, 1900–2100. *Building Research & Information*, *36*(5), 412–425. https://doi.org/10.1080/09613210802184312

Sartori, I., Sandberg, N. H., & Brattebø, H. (2016). Dynamic building stock modelling: General algorithm and exemplification for Norway. *Energy and Buildings*, *132*, 13–25. https://doi.org/10.1016/j.enbuild.2016.05.098

Schebek, L., Schnitzer, B., Blesinger, D., Köhn, A., Miekley, B., Linke, H. J., Lohmann, A., Motzko, C., & Seemann, A. (2017). Material stocks of the non-residential building sector: The case of the Rhine-Main area. *Resources, Conservation and Recycling*, *123*, 24–36. https://doi.org/10.1016/j.resconrec.2016.06.001

Schiller, G., Lützkendorf, T., Gruhler, K., Lehmann, I., Mörmann, K., Knappe, F., & Muchow, N. (2019). Material Flows in Buildings' Life Cycle and Regions-Material Inventories to Support Planning Towards Circular Economy [Issue: 1 ISSN: 17551315]. *IOP Conference Series: Earth and Environmental Science*, *290*. https://doi.org/10.1088/1755-1315/290/1/012031

Schiller, G., Lützkendorf, T., Lehmann, I., Mörmann, K., Gruhler, K., & Knappe, F. (2020). Management system for building materials as a basis for closed loop material flow analysis considering material efficiency and climate change mitigation [Issue: 2 ISSN: 17551315]. *IOP Conference Series: Earth and Environmental Science*, *588*. https://doi.org/10.1088/1755-1315/588/2/022010

Schiller, G., Deilmann, C., Gruhler, K., Röhm, P., Reichenbach, J., Baumann, J., & Günther, M. (2010). *Ermittlung von Ressourcenschonungs-potenzialen bei der Verwertung von Bauabfällen und Erarbeitung von Empfehlungen zu deren Nutzung in Kooperation mit*. Umweltbundesamt. Retrieved March 19, 2023, from https://www.umweltbundesamt.de/publikationen/ermittlung-von-ressourcenschonungspotenzialen-bei

Schiller, G., Gruhler, K., & Ortlepp, R. (2018). Quantification of anthropogenic metabolism using spatially differentiated continuous MFA. *Change and Adaptation in Socio-Ecological Systems*, *3*(1). https://doi.org/10.1515/cass-2017-0011

Schiller, G., Müller, F., & Ortlepp, R. (2017). Mapping the anthropogenic stock in Germany: Metabolic evidence for a circular economy. *Resources, Conservation and Recycling*, *123*, 93–107. https://doi.org/10.1016/j.resconrec.2016.08.007

Schiller, G., Ortlepp, R., Krauß, N., Steger, S., Schütz, H., Acosta Fernández, J., Reichenbach, J., Wagner, J., & Baumann, J. (2015). *Kartierung des anthropogenen Lagers in Deutschland zur Optimierung der Sekundärrohstoffwirtschaft*.

Stadt Hamburg. (2022). Hamburgs Klimaplan. Machbarkeitsstudie als Meilenstein: Hamburgs Wohngebäude werden bis 2045 klimaneutral. Retrieved March 3, 2023, from https://www.hamburg.de/pressearchiv-fhh/16571902/2022-10-11-bsw-hamburgs-gebaeude-klimaneutral/

Stadt Hamburg. (2023). Das Hamburger 3D Stadtmodell. Retrieved November 17, 2023, from https://www.hamburg.de/bsw/geodaten-des-lgv/7615476/3d-stadtmodell/

Tanikawa, H., Fishman, T., Okuoka, K., & Sugimoto, K. (2015). The Weight of Society Over Time and Space: A Comprehensive Account of the Construction Material Stock of Japan, 1945–2010. *Journal of Industrial Ecology*, *19*(5), 778–791. https://doi.org/10.1111/jiec.12284

Tanikawa, H., & Hashimoto, S. (2009). Urban stock over time: Spatial material stock analysis using 4d-GIS. *Building Research & Information*, *37*(5-6), 483–502. https://doi.org/10.1080/09613210903169394

Umweltbundesamt. (2022a). Asbest. Retrieved October 19, 2023, from https://www.umweltbundesamt.de/themen/gesundheit/umwelteinfluesse-auf-den-menschen/chemische-stoffe/asbest

Umweltbundesamt. (2022b). *Kartierung des anthropogenen Lagers III (KartAL III) Abschlussbericht* [ISSN: 1862-4804].

US EPA. (2023). Learn About Asbestos. Retrieved October 19, 2023, from https://www.epa.gov/asbestos/learn-about-asbestos

Verhagen, T. J., Sauer, M. L., Voet, E. v. d., & Sprecher, B. (2021). Matching demolition and construction material flows, an urban mining case study. *Sustainability (Switzerland)*, *13*(2), 1–14. https://doi.org/10.3390/su13020653

Volk, R., Müller, R., Reinhardt, J., & Schultmann, F. (2019). An Integrated Material Flows, Stakeholders and Policies Approach to Identify and Exploit Regional Resource Potentials. *Ecological Economics*, *161*, 292–320. https://doi.org/10.1016/j.ecolecon.2019.03.020

Wartenberg, D., Greenberg, M., & Lanthrop, R. (1993). Identification and characterization of populations living near high-voltage transmission lines: A pilot study. *Environmental Health Perspectives*, *101*(7), 626–632. https://doi.org/https://doi.org/10.1289/ehp.93101626

Wiedenhofer, D., Steinberger, J. K., Eisenmenger, N., & Haas, W. (2015). Maintenance and Expansion: Modeling Material Stocks and Flows for Residential Buildings and Transportation Networks in the EU25. *Journal of Industrial Ecology*, *19*(4), 538–551. https://doi.org/10.1111/jiec.12216

A

Material Groups of the Material Intensities

Table A.1: Material groups and the underlaying list of materials.

Material group	Material
Concrete	Concrete, lightweigth concrete
Bricks	Bricks, bricks with insulation, brick cover/roof tiles,
Other minerals	Calcareous plaster mortar, plaster and mortar containing gypsum and anhydrite, clay and loamy plaster and mortar, plasters with synthetic components, calcareous screeds, screeds containing gypsum and anhydrite, dry screed containing gypsum and anhydrite, screeds with synthetic components, sand-lime bricks, aerated concrete blocks, concrete blocks, mud bricks, (gypsum) plasterboards, mineral building boards, mineral thermal insulation materials, concrete roof tile covering, fiber cement roofing, slate cover, substrate layer (green roof), mineral fillings, glass, natural bricks, other mineral building materials.
Lumber and processed wood	timber/lumber, processed wood
Other renewable materials	Renewable thermal insulation materials, straw/reed cover, other materials non-mineral
Plastics	Petroleum-based thermal insulation materials, plastic roofing, petroleum-based coverings, geomembranes
Bituminous materials	Bitumen roofing, bituminous coverings, waterproofing membranes
Ferrous metals	Metal roofing, ferrous metals
Non-ferrous metals	Coverings containing aluminium, sealing membranes, aluminium, copper, other non-ferrous metals

B

Material Intensity Values

The material intensity values for all classes except garages are obtained from the available Excel files in the online database of IÖR (2023), calculating values in kg per m^2 through the division of material quantities by the gross floor area. The material intensity for garages is an average of the value used by Haberl et al. (2021) and calculations of this study, supported by knowledge of an expert in the field (R. Erps, personal communication, 12.10.2023) and a Google Street View exploration (Google Maps, 2023).

Table B.1: Applied material intensity values obtained from IÖR (2023) and own calculations.

Classification	Age cohort	Classification in code (if different)	Concrete	Brick	Other minerals	Lumber & processed wood	Other renewable materials	Plastics	Bituminous	FE-metals	Non FE-metals	Unit	Total MI
SFH (single-family house)	before 1919	SFH0	310.140	181.629	599.560	40.648	0.027	0	0.164	20.329	0	[kg/m^2]	1152.50
	1919-1948	SFH1	310.140	181.629	599.560	40.648	0.027	0	0.164	20.329	0	[kg/m^2]	1152.50
	1949-1978	SFH2	610.493	75.141	730.514	17.513	3.182	2.770	0.474	65.001	0.309	[kg/m^2]	1505.40
	1979-1990	SFH3	600.189	82.664	700.044	18.603	5.475	3.168	0.750	64.410	0.321	[kg/m^2]	1475.62
	after 1990	SFH4	531.046	104.955	567.574	20.977	5.298	4.631	0.955	62.308	0	[kg/m^2]	1297.74
MFH (multi-family house)	before 1919	MFH0	76.471	537.682	592.786	37.397	0.241	0.000	0.519	1.225	0	[kg/m^2]	1246.32
	1919-1948	MFH1	185.830	522.917	456.237	11.646	0	0.103	1.361	32.099	0	[kg/m^2]	1210.19
	1949-1978	MFH2	693.662	160.541	333.994	6.073	0.084	1.342	2.358	72.012	0	[kg/m^2]	1270.07
	1979-1990	MFH3	760.627	83.105	456.180	6.009	0.121	3.865	0.662	92.372	0	[kg/m^2]	1402.94
	after 1990	MFH4	580.630	90.719	555.409	13.019	1.192	4.850	0.213	74.605	0	[kg/m^2]	1320.64
garage	-	-	732.231	79.473	450.406	28.032	0	0	4.537	31.641	0.213	[kg/m^2]	1052.30
institutional building	-	-	743.825	124.559	503.969	17.655	0.005	2.912	0.823	76.918	3.375	[kg/m^2]	1474.04
office building	-	-	823.873	109.627	554.789	27.715	0.011	2.670	0.692	87.851	4.605	[kg/m^2]	1611.83
agricultural/farm building	-	-	646.193	29.358	1174.307	41.025	0.000	2.170	1.401	108.480	0.755	[kg/m^2]	2003.69
factory/workshop building	-	-	902.630	109.210	882.620	12.732	0.003	3.784	2.934	123.002	5.406	[kg/m^2]	2042.32
trade building	-	-	951.213	88.147	711.825	13.174	0.029	3.602	0.265	94.431	2.825	[kg/m^2]	1865.51
warehouse building	-	-	977.455	46.968	946.830	5.901	0	3.574	0.551	145.993	2.557	[kg/m^2]	2129.83
hotel/restaurant	-	-	829.822	145.538	631.333	19.948	0.025	3.085	0.592	93.312	1.813	[kg/m^2]	1725.47
other non-agricultural building	-	-	1456.261	5.218	531.773	0	0	0.410	2.669	140.724	0.133	[kg/m^2]	2137.19
other non-residential building	-	-	1056.362	144.586	660.742	26.092	0.005	3.290	0.634	111.930	3.898	[kg/m^2]	2007.54

C

Data Examination

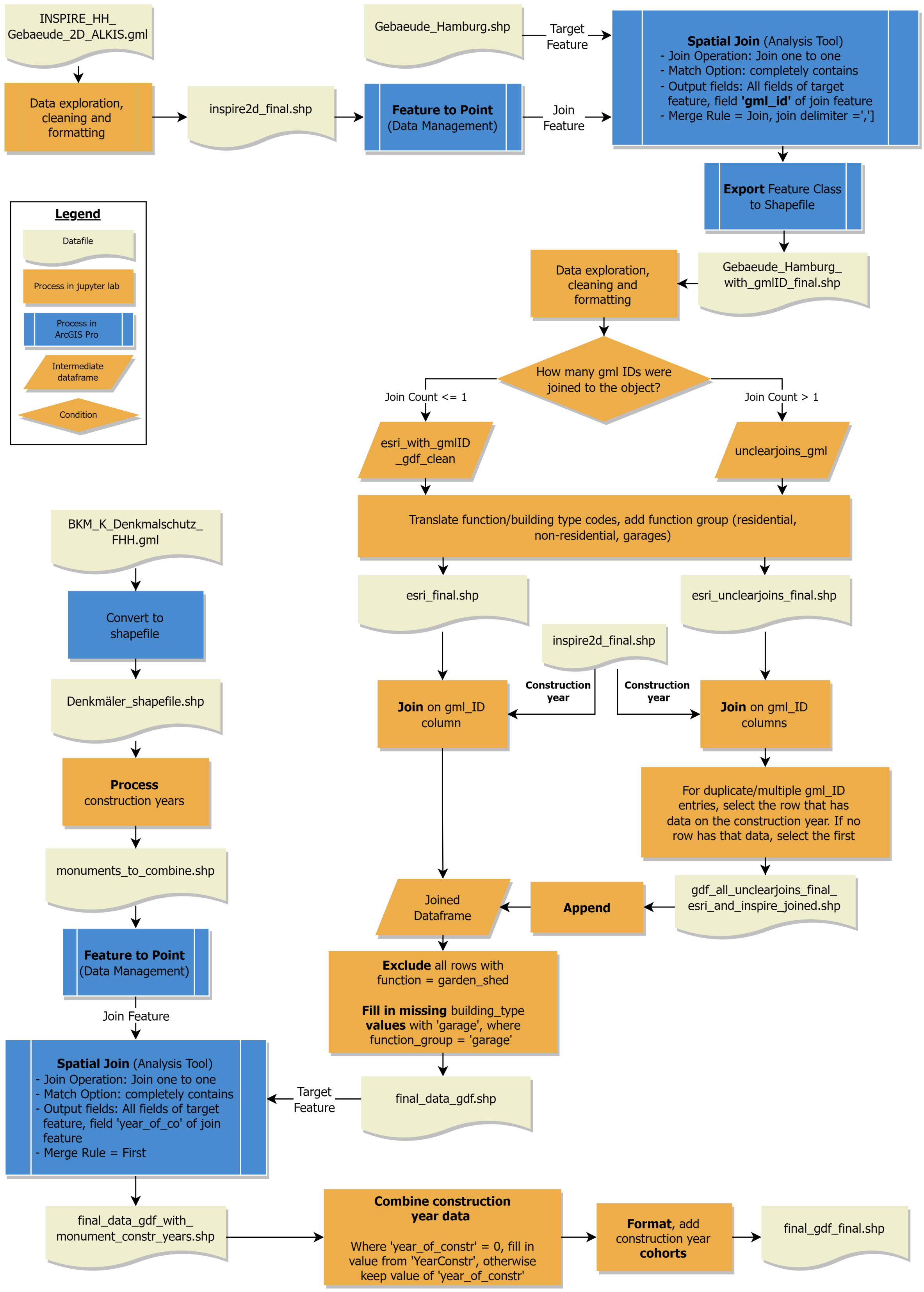

Figure C.1: Detailed flowchart of the examination step. Authors visualisation.

D

Translation of Function Codes

Data on functions in dataset [2] is present in the format of standardised codes. These are translated with a standardised key (AdV, 2018).

Table D.1: Translation of function codes in dataset [2].

German	English
'1010': 'Wohnhaus',	'1010': 'residential_building',
'1020': 'Wohnheim',	'1020': 'residential_home',
'1100': 'Gemischt genutztes Gebäude mit Wohnen',	'1100': 'mixed_use_with_residential',
'1110': 'Wohngebäude mit Gemeinbedarf',	'1110': 'res_building_with_public_use',
'1120': 'Wohngebäude mit Handel und Dienstleistungen',	'1120': 'res_building_with_trade_and_service',
'1130': 'Wohngebäude mit Gewerbe und Industrie',	'1130': 'res_building_with_commerce_and_industry',
'1210': 'Land- und forstwirtschaftliches Wohngebäude',	'1210': 'res_building_with_agriculture_and_forestry',
'1220': 'Land- und forstwirtschaftliches Wohn- und Betriebsgebäude',	'1220': 'res_and_farm_building_for_agriculture_and_forestry',
'1311': 'Ferienhaus',	'1311': 'holiday_home',
'1312': 'Wochenendhaus',	'1312': 'weekend_house',
'1313': 'Gartenhaus',	'1313': 'garden_shed',
'2010': 'Gebäude für Handel und Dienstleistungen',	'2010': 'non_res_building_for_trade_and_services',
'2020': 'Bürogebäude',	'2020': 'office_building',
'2050': 'Geschäftsgebäude',	'2050': 'commercial_building',
'2053': 'Markthalle',	'2053': 'markethall',
'2060': 'Messehalle',	'2060': 'exhibition_hall',
'2071': 'Hotel, Motel, Pension',	'2071': 'hotel_motel_guesthouse',
'2072': 'Jugendherberge',	'2072': 'hostel',
'2074': 'Campingplatzgebäude',	'2074': 'campground_building',
'2080': 'Gebäude für Bewirtung',	'2080': 'hospitality_building',
'2090': 'Freizeit- und Vergnügungsstätte',	'2090': 'leisure_and_entertainment_facility',
'2110': 'Produktionsgebäude',	'2110': 'production_facility',
'2112': 'Betriebsgebäude',	'2112': 'company_building',
'2113': 'Brauerei',	'2113': 'brewery',
'2120': 'Werkstatt',	'2120': 'workshop',
'2130': 'Tankstelle',	'2130': 'gas_station',
'2131': 'Waschstraße, Waschanlage, Waschhalle',	'2131': 'car_wash',
'2140': 'Gebäude für Vorratshaltung',	'2140': 'storage_building',
'2150': 'Speditionsgebäude',	'2150': 'freight_building',
'2160': 'Gebäude für Forschungszwecke',	'2160': 'building_for_research_purposes',
'2213': 'Schöpfwerk',	'2213': 'pump_station',
'2310': 'Gebäude für Handel und Dienstleistung mit Wohnen',	'2310': 'non_res_building_for_trade_and_services_with_res',
'2320': 'Gebäude für Gewerbe und Industrie mit Wohnen',	'2320': 'commercial_and_industrial_building_with_res',

German	English
'2410': 'Betriebsgebäude für Straßenverkehr',	'2410': 'operational_building_road_traffic',
'2420': 'Betriebsgebäude für Schienenverkehr',	'2420': 'operational_building_rail_traffic',
'2430': 'Betriebsgebäude für Flugverkehr',	'2430': 'operational_building_air_traffic',
'2431': 'Flugzeughalle',	'2431': 'aircraft_hanger',
'2440': 'Betriebsgebäude für Schiffsverkehr',	'2440': 'operational_building_shipping',
'2441': 'Werft (Halle)',	'2441': 'shipyard',
'2443': 'Betriebsgebäude zur Schleuse',	'2443': 'operational_building_sluice',
'2444': 'Bootshaus',	'2444': 'boathouse',
'2445': 'Betriebsgebäude zur Schleuse',	'2445': 'operational_building_sluice',
'2446': 'Betriebsgebäude zur Schleuse',	'2446': 'operational_building_sluice',
'2447': 'Betriebsgebäude zur Schleuse',	'2447': 'operational_building_sluice',
'2448': 'Betriebsgebäude zur Schleuse',	'2448': 'operational_building_sluice',
'2449': 'Betriebsgebäude zur Schleuse',	'2449': 'operational_building_sluice',
'2450': 'Betriebsgebäude zur Schleuse',	'2450': 'operational_building_sluice',
'2451': 'Betriebsgebäude zur Schleuse',	'2451': 'operational_building_sluice',
'2452': 'Betriebsgebäude zur Schleuse',	'2452': 'operational_building_sluice',
'2453': 'Betriebsgebäude zur Schleuse',	'2453': 'operational_building_sluice',
'2454': 'Betriebsgebäude zur Schleuse',	'2454': 'operational_building_sluice',
'2455': 'Betriebsgebäude zur Schleuse',	'2455': 'operational_building_sluice',
'2456': 'Betriebsgebäude zur Schleuse',	'2456': 'operational_building_sluice',
'2457': 'Betriebsgebäude zur Schleuse',	'2457': 'operational_building_sluice',
'2458': 'Betriebsgebäude zur Schleuse',	'2458': 'operational_building_sluice',
'2459': 'Betriebsgebäude zur Schleuse',	'2459': 'operational_building_sluice',
'2460': 'Gebäude zum Parken',	'2460': 'building_for_parking',
'2461': 'Parkhaus',	'2461': 'parking_garage',
'2462': 'Parkdeck',	'2462': 'parking_deck',
'2463': 'Garage',	'2463': 'garage',
'2464': 'Fahrzeughalle',	'2464': 'vehicle_depot',
'2465': 'Tiefgarage',	'2465': 'underground_parking',
'2500': 'Gebäude zur Versorgung',	'2500': 'supply_building_general',
'2510': 'Gebäude zur Wasserversorgung',	'2510': 'water_supply_building',
'2520': 'Gebäude zur Elektrizitätsversorgung',	'2520': 'electricity_supply_building',
'2540': 'Gebäude für Fernmeldewesen',	'2540': 'telecommunications_building',
'2560': 'Gebäude an unterirdischen Leitungen',	'2560': 'building_on_underground_lines',
'2570': 'Gebäude zur Gasversorgung',	'2570': 'gas_supply_building',
'2580': 'Heizwerk',	'2580': 'heating_plant',
'2590': 'Gebäude zur Versorgungsanlage',	'2590': 'building_for_supply_system',
'2611': 'Gebäude der Kläranlage',	'2611': 'wastewater_treatment_plant_building',
'2612': 'Toilette',	'2612': 'toilet',
'2620': 'Gebäude zur Abfallbehandlung',	'2620': 'waste_treatment_building',
'2621': 'Müllbunker',	'2621': 'waster_bunker',
'2622': 'Gebäude zur Müllverbrennung',	'2622': 'waste_incineration_building',
'2720': 'Land- und forstwirtschaftliches Betriebsgebäude',	'2720': 'agricultural_and_forestry_farm_building',
'2724': 'Stall',	'2724': 'stable',
'2726': 'Scheune und Stall',	'2726': 'barn_and_stable',
'2728': 'Reithalle',	'2728': 'indoor_riding_arena',
'2740': 'Treibhaus, Gewächshaus',	'2740': 'greenhouse',
'2742': 'Gewächshaus, verschiebbar',	'2742': 'greenhouse_movable',
'3010': 'Verwaltungsgebäude',	'3010': 'administration_building',
'3012': 'Rathaus',	'3012': 'town_hall',
'3014': 'Zollamt',	'3014': 'customs_office',
'3015': 'Gericht',	'3015': 'court',
'3016': 'Botschaft, Konsulat',	'3016': 'embassy_consulate',
'3020': 'Gebäude für Bildung und Forschung',	'3020': 'education_and_research_building',
'3021': 'Allgemein bildende Schule',	'3021': 'school_for_general_education',
'3022': 'Berufsbildende Schule',	'3022': 'vocational_school',
'3023': 'Hochschulgebäude (Fachhochschule, Universität)',	'3023': 'university_or_technical_college',
'3024': 'Forschungsinstitut',	'3024': 'research_institute',
'3030': 'Gebäude für kulturelle Zwecke',	'3030': 'building_for_cultural_purpose',
'3031': 'Schloss',	'3031': 'castle',
'3032': 'Theater, Oper',	'3032': 'theatre_opera',
'3033': 'Konzertgebäude',	'3033': 'concerthall',
'3034': 'Museum',	'3034': 'museum',
'3035': 'Rundfunk, Fernsehen',	'3035': 'radio_television_studio',
'3036': 'Veranstaltungsgebäude',	'3036': 'event_location',

German	English
'3037': 'Bibliothek, Bücherei',	'3037': 'library',
'3040': 'Gebäude für religiöse Zwecke',	'3040': 'building_for_religious_purpose',
'3041': 'Kirche',	'3041': 'church',
'3042': 'Synagoge',	'3042': 'synagogue',
'3043': 'Kapelle',	'3043': 'chapel',
'3044': 'Gemeindehaus',	'3044': 'community_centre',
'3045': 'Gotteshaus',	'3045': 'place_of_worship',
'3046': 'Moschee',	'3046': 'mosque',
'3048': 'Kloster',	'3048': 'monastery_convent',
'3050': 'Gebäude für Gesundheitswesen',	'3050': 'health_care_building',
'3051': 'Krankenhaus',	'3051': 'hospital',
'3060': 'Gebäude für soziale Zwecke',	'3060': 'building_for_social_purpose',
'3061': 'Jugendfreizeitheim',	'3061': 'youth_leisure_centre',
'3062': 'Freizeit-, Vereinsheim, Dorfgemeinschafts-, Bürgerhaus',	'3062': 'leisure_or_village_community_centre',
'3065': 'Kinderkrippe, Kindergarten, Kindertagesstätte',	'3065': 'kindergarten_day_care_center',
'3070': 'Gebäude für Sicherheit und Ordnung',	'3070': 'building_for_security_and_order',
'3071': 'Polizei',	'3071': 'police_station',
'3072': 'Feuerwehr',	'3072': 'fire_station',
'3073': 'Kaserne',	'3073': 'barracks',
'3074': 'Schutzbunker',	'3074': 'bunker',
'3075': Justizvollzugsanstalt,	'3075': 'prison',
'3080': 'Friedhofsgebäude',	'3080': 'cemetery_building',
'3082': 'Krematorium',	'3082': 'crematorium',
'3091': 'Bahnhofsgebäude',	'3091': 'trainstation',
'3092': 'Flughafengebäude',	'3092': 'airport',
'3097': 'Gebäude zum Busbahnhof',	'3097': 'busterminal',
'3098': 'Empfangsgebäude Schifffahrt',	'3098': 'reception_building_shipping',
'3210': 'Gebäude für Sportzwecke',	'3210': 'building_for_sports_purposes',
'3211': 'Sport-, Turnhalle',	'3211': 'sports_hall_gym',
'3212': 'Gebäude zum Sportplatz',	'3212': 'sports_field_building',
'3221': 'Hallenbad',	'3221': 'indoor_swimming_pool',
'3222': 'Gebäude im Freibad',	'3222': 'outdoor_swimming_pool_building',
'3230': 'Gebäude im Stadion',	'3230': 'stadium_building',
'3260': 'Gebäude im Zoo',	'3260': 'zoo_building',
'3270': 'Gebäude im botanischen Garten',	'3270': 'botanical_garden_building',
'3290': 'Touristisches Informationszentrum',	'3290': 'tourist_information_centre',

E

Sorting of the Function Types into Function Groups

The data on functions in dataset [2] is highly detailed. In order to aggregate functions into the three overarching groups of residential buildings, non-residential buildings and garages, the sorting is defined as found in the table below.

Table E.1: Sorting of function types into function groups.

residential_list	**non_residential_list**	**garage_list**
'residential_building'	'non_res_building_for_trade_and_services'	'garage'
'residential_home'	'office_building'	
'mixed_use_with_residential'	'commercial_building'	
'res_building_with_public_use'	'production_facility'	
'res_building_with_trade_and_service'	'company_building'	
'res_building_with_commerce_and_industry'	'brewery'	
'res_building_with_agriculture_and_forestry'	'workshop'	
'res_and_farm_building_for_agriculture_and_forestry'	'gas_station'	
'weekend_house'	'car_wash'	
'holiday_home'	'storage_building'	
	'freight_building'	
	'building_for_research_purposes'	
	'pump_station'	
	'non_res_building_for_trade_and_services_with_res'	
	'commercial_and_industrial_building_with_res'	
	'operational_building_road_traffic'	
	'operational_building_rail_traffic'	
	'operational_building_air_traffic'	
	'operational_building_shipping'	
	'shipyard'	
	'operational_building_sluice'	
	'boathouse'	
	'building_for_parking'	
	'parking_garage'	
	'parking_deck'	

residential_list	non_residential_list	garage_list
	'vehicle_depot'	
	'underground_parking'	
	'water_supply_building'	
	'electricity_supply_building'	
	'telecommunications_building'	
	'building_on_underground_lines'	
	'gas_supply_building'	
	'heating_plant'	
	'building_for_supply_system'	
	'wastewater_treatment_plant_building'	
	'toilet'	
	'waste_treatment_building'	
	'waster_bunker'	
	'waste_incineration_building'	
	'agricultural_and_forestry_farm_building'	
	'stable'	
	'barn_and_stable'	
	'greenhouse'	
	'administration_building'	
	'town_hall'	
	'customs_office'	
	'court'	
	'education_and_research_building'	
	'school_for_general_education'	
	'university_or_technical_college'	
	'building_for_cultural_purpose'	
	'museum'	
	'event_location'	
	'library'	
	'building_for_religious_purpose'	
	'church'	
	'chapel'	
	'place_of_worship'	
	'mosque'	
	'health_care_building'	
	'hospital'	
	'building_for_social_purpose'	
	'youth_leisure_centre'	
	'building_for_security_and_order'	
	'police_station'	
	'fire_station'	
	'bunker'	
	'cemetery_building'	
	'train_station'	
	'bus_station_building'	
	'building_for_sports_purposes'	
	'sports_hall_gym'	
	'sports_field_building'	
	'indoor_swimming_pool'	
	'outdoor_swimming_pool_building'	
	'zoo_building'	
	'markethall'	
	'exhibition_hall'	
	'campground_building'	
	'aircraft_hanger'	
	'supply_building_general'	

residential_list	non_residential_list	garage_list
	'indoor_riding_arena'	
	'greenhouse_movable'	
	'embassy_consulate'	
	'vocational_school'	
	'research_institute'	
	'castle'	
	'theatre_opera'	
	'concerthall'	
	'radio_television_studio'	
	'synagogue'	
	'barracks'	
	'prison'	
	'crematorium'	
	'airport'	
	'reception_building_shipping'	
	'stadium_building'	
	'botanical_garden_building'	
	'tourist_information_centre'	
	'hotel_motel_guesthouse'	
	'hostel'	
	'hospitality_building'	
	'leisure_and_entertainment_facility'	
	'community_centre'	
	'leisure_or_village_community_centre'	
	'kindergarten_day_care_center'	

F

Translation and Sorting of Available Building Types

Table F.1: Translation and sorting of available building type categories.

German	English (direct translation)	English (chosen translation)
'1100': 'Freistehendes Einzelgebäude',	'1100': 'detached_individual',	'1100': 'detached_individual',
'1200': 'Freistehender Gebäudeblock',	'1200': 'detached_block',	'1200': 'detached_block',
'1300': 'Einzelgarage',	'1300': 'single_garage',	'1300': 'garage',
'1400': 'Doppelgarage',	'1400': 'twin_garage',	'1400': 'garage',
'1500': 'Sammelgarage',	'1500': 'multi_garage',	'1500': 'garage',
'2100': 'Doppelhaushälfte',	'2100': 'semi-detached',	'2100': 'semi-detached',
'2200': 'Reihenhaus',	'2200': 'terraced',	'2200': 'terraced',
'2400': 'Gruppenhaus',	'2400': 'terraced',	'2400': 'terraced',
'2500': 'Gebäudeblock in geschlossener Bauweise',	'2500': 'terraced_block',	'2500': 'terraced_block',

G

Re-Classification of Residential Buildings to Fit MI Classes

Table G.1: Re-classification of building typology for residential buildings (SFH or MFH).

Number of floors	Current building type	Surface area	Classification
>= 4	-	-	MFH
3	terraced_block	-	MFH
	detached_block	-	MFH
	detached_individual	<= 250 m^2	SFH
		> 250 m^2	MFH
	semi_detached	<= 250 m^2	SFH
		> 250 m^2	MFH
	terraced	<= 130 m^2	SFH
		> 130 m^2	MFH
	no BuildType value	<= 200 m^2	SFH
		> 200 m^2	MFH
2	terraced_block	-	MFH
	detached_block	-	MFH
	detached_individual	< 400 m^2	SFH
		>= 400 m^2	MFH
	semi_detached	< 400 m^2	SFH
		>= 400 m^2	MFH
	terraced	-	SFH
		one object > 200 m^2	MFH
	no BuildType value	< 400 m^2	SFH
		>= 400 m^2	MFH
1	terraced_block	-	MFH
	detached_block	-	MFH
	detached_individual	< 400 m^2	SFH
		>= 400 m^2	MFH
	semi_detached	< 400 m^2	SFH
		>= 400 m^2	MFH
	terraced	-	SFH
	no BuildType value	>= 300 m^2	MFH
		< 300 m^2	SFH

H

Sorting of Non-Residential Functions into MI Classes

Table H.1: Sorting of non-residential functions into material intensity classes.

Non-residential group	Assorted values
institutional building	hospital','health_care_building'
office building	'office_building','company_building','administration_building','town_hall','customs_office', 'embassy_consulate','court','castle'
agricultural/farm building	'agricultural_and_forestry_farm_building','stable','barn_and_stable','greenhouse', 'greenhouse_movable'
factory/workshop building	police_station','fire_station','building_for_security_and_order','bunker','barracks','prison', 'production_facility','workshop','pump_station','water_supply_building', 'electricity_supply_building','telecommunications_building','building_on_underground_lines', 'gas_supply_building','heating_plant','building_for_supply_system', 'wastewater_treatment_plant_building','waste_treatment_building', 'waster_bunker', 'waste_incineration_building','supply_building_general'
trade building	commercial_building','non_res_building_for_trade_and_services','car_wash','gas_station', 'non_res_building_for_trade_and_services_with_res', 'commercial_and_industrial_building_with_res','markethall','brewery'
warehouse building	'storage_building','freight_building'
hotel/restaurant	'hotel_motel_guesthouse','hostel','hospitality_building','campground_building'
other non-agricultural building	underground_parking','parking_garage','parking_deck','trainstation','busterminal', 'reception_building_shipping','operational_building_road_traffic', 'operational_building_rail_traffic','operational_building_air_traffic', 'operational_building_shipping','building_for_parking','vehicle_depot', 'operational_building_sluice','boathouse','shipyard','airport','aircraft_hanger', 'leisure_and_entertainment_facility','radio_television_studio'
other non-residential building	stadium_building','kindergarten_day_care_center','vocational_school','research_institute', 'library','chapel','building_for_religious_purpose','church','place_of_worship','mosque', 'synagogue','indoor_swimming_pool','outdoor_swimming_pool_building', 'youth_leisure_centre','leisure_or_village_community_centre','community_centre', 'theatre_opera','concerthall','botanical_garden_building','exhibition_hall', 'education_and_research_building','school_for_general_education', 'university_or_technical_college','building_for_research_purposes', 'building_for_cultural_purpose','museum','event_location','building_for_social_purpose', 'building_for_sports_purposes','sports_hall_gym','sports_field_building','zoo_building', 'indoor_riding_arena','tourist_information_centre','toilet','crematorium','cemetery_building'

I

Iteration Steps During Construction Year Allocation

Table I.1: Allocation iterations for residential buildings.

Iteration	Applied buffer size [m]	Objects with known year	Objects missing year	% missing	improved by [%]	Number of years assigned during iteration	Sum check
0 (baseline)	-	123,826	106,706	46.29%	-	-	230,532
after 1st	1	139,720	90,812	39.39%	6.9%	15,894	230,532
after 2nd	1	143,209	87,323	37.88%	1.5%	3,489	230,532
after 3rd	1	144,696	85,836	37.23%	0.6%	1,487	230,532
after 4th	5	153,590	76,942	33.38%	3.9%	8,894	230,532
after 5th	5	156,087	74,445	32.29%	1.1%	2,497	230,532
after 6th	10	179,892	50,640	21.97%	10.3%	23,805	230,532
after 7th	10	189,223	41,309	17.92%	4.0%	9,331	230,532
after 8th	10	192,805	37,727	16.37%	1.6%	3,582	230,532
after 9th	15	204,204	26,328	11.42%	4.9%	11,399	230,532
after 10th	15	209,159	21,373	9.27%	2.1%	4,955	230,532
after 11th	15	211,082	19,450	8.44%	0.8%	1,923	230,532
after 12th	20	216,955	13,577	5.89%	2.5%	5,873	230,532
after 13th	20	219,556	10,976	4.76%	1.1%	2,601	230,532
after 14th	25	222,664	7,868	3.41%	1.3%	3,108	230,532
after 15h	25	223,932	6,600	2.86%	0.6%	1,268	230,532
after 16th	30	225,419	5,113	2.22%	0.6%	1,487	230,532
after 17th	35	226,633	3,899	1.69%	0.5%	1,214	230,532
after 18th	40	227,401	3,131	1.36%	0.3%	768	230,532
after 19th	50	228,097	2,435	1.06%	0.3%	696	230,532
after 20th	100	229,257	1,275	0.55%	0.5%	1,160	230,532
after 21st	250	230,170	362	0.16%	0.4%	913	230,532
after 22nd	400	230,398	134	0.06%	0.1%	228	230,532
after 23rd	500	230,497	35	0.02%	0.0%	99	230,532
after 24th	1000	230,529	3	0.00%	0.0%	32	230,532
after 25th	3000	230,532	-	0.00%	0.0%	3	230,532

Table I.2: Allocation iterations for non-residential buildings. [* allocation also from residential buildings.]

Iteration	Applied buffer size [m]	Objects with known year	Objects missing year	% missing	improved by [%]	Number of years assigned during iteration	Sum check
0 (baseline)	-	9,922	32,342	76.52%	-	-	42,264
after 1st	1	11,845	30,419	71.97%	4.5%	1,923	42,264
after 2nd	1	12,504	29,760	70.41%	1.6%	659	42,264
after 3rd	5	13,669	28,595	67.66%	2.8%	1,165	42,264
after 4th	10	15,778	26,486	62.67%	5.0%	2,109	42,264
after 5th	10	16,815	25,449	60.21%	2.5%	1,037	42,264
after 6th	20	19,786	22,478	53.18%	7.0%	2,971	42,264
after 7th	20	21,412	20,852	49.34%	3.8%	1,626	42,264
after 8th	20	22,167	20,097	47.55%	1.8%	755	42,264
after 9th	40	25,875	16,389	38.78%	8.8%	3,708	42,264
after 10th	40	28,128	14,136	33.45%	5.3%	2,253	42,264
after 11th	40	28,972	13,292	31.45%	2.0%	844	42,264
after 12th	60	31,102	11,162	26.41%	5.0%	2,130	42,264
after 13th	60	32,676	9,588	22.69%	3.7%	1,574	42,264
after 14th	80	34,458	7,806	18.47%	4.2%	1,782	42,264
after 15th	80	35,541	6,723	15.91%	2.6%	1,083	42,264
after 16th*	10	38,393	3,871	9.16%	6.7%	2,852	42,264
after 17th	10	38,838	3,426	8.11%	1.1%	445	42,264
after 18th	20	39,814	2,450	5.80%	2.3%	976	42,264
after 19th	40	40,758	1,506	3.56%	2.2%	944	42,264
after 20th	60	41,169	1,095	2.59%	1.0%	411	42,264
after 21st	80	41,388	876	2.07%	0.5%	219	42,264
after 22nd	100	41,610	654	1.55%	0.5%	222	42,264
after 23rd	200	42,007	257	0.61%	0.9%	397	42,264
after 24th	400	42,227	37	0.09%	0.5%	220	42,264
after 25th	800	42,259	5	0.01%	0.1%	32	42,264
after 26th	2000	42,264	-	0.00%	0.0%	5	42,264

Table I.3: Allocation iterations for garages.

Iteration	Applied buffer size [m]	Objects with known year	Objects missing year	% missing	improved by [%]	Number of years assigned during iteration	Sum check
0 (baseline)	-	7,886	53,339	87.12%	-	-	61,225
after 1st	1	30,726	30,499	49.81%	37.3%	22,840	61,225
after 2nd	5	46,210	15,015	24.52%	25.3%	15,484	61,225
after 3rd	10	55,442	5,783	9.45%	15.1%	9,232	61,225
after 4th	15	58,996	2,229	3.64%	5.8%	3,554	61,225
after 5th	20	60,263	962	1.57%	2.1%	1,267	61,225
after 6th	25	60,788	437	0.71%	0.9%	525	61,225
after 7th	50	61,119	106	0.17%	0.5%	331	61,225
after 8th	100	61,183	42	0.07%	0.1%	64	61,225
after 9th	200	61,216	9	0.01%	0.1%	33	61,225
after 10th	250	61,225	-	0.00%	0.0%	9	61,225

J

Exemplary Display of the Truncated Weibull PDF Used for Lifetime Sampling and the Correlating Distribution of the Random Samples

Residential Buildings and Garages

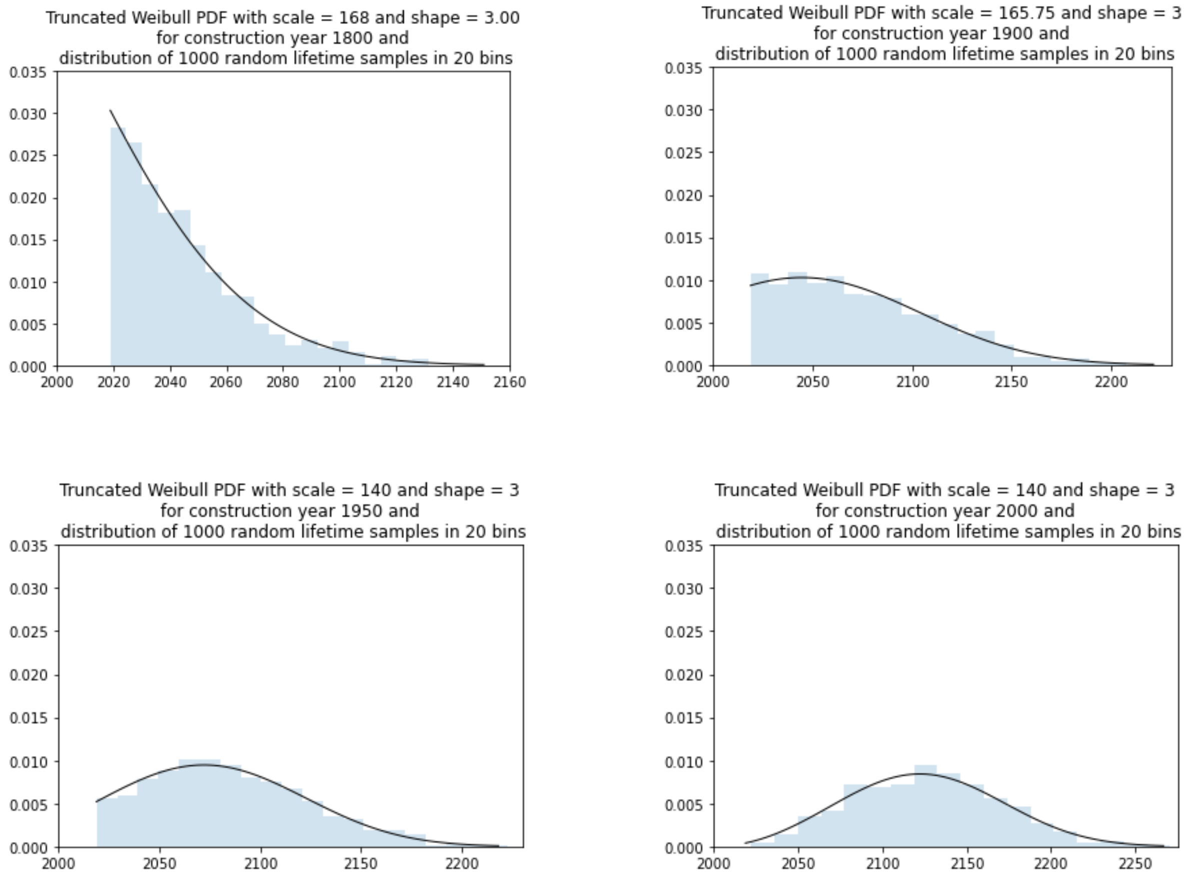

Figure J.1: Truncated Weibull PDF and correlating distribution of 1000 random samples for residential buildings and garages. These are four examples for buildings with construction years 1800, 1900, 1950 and 2000, applying the values stated in Table 3.2.

Non-Residential Buildings

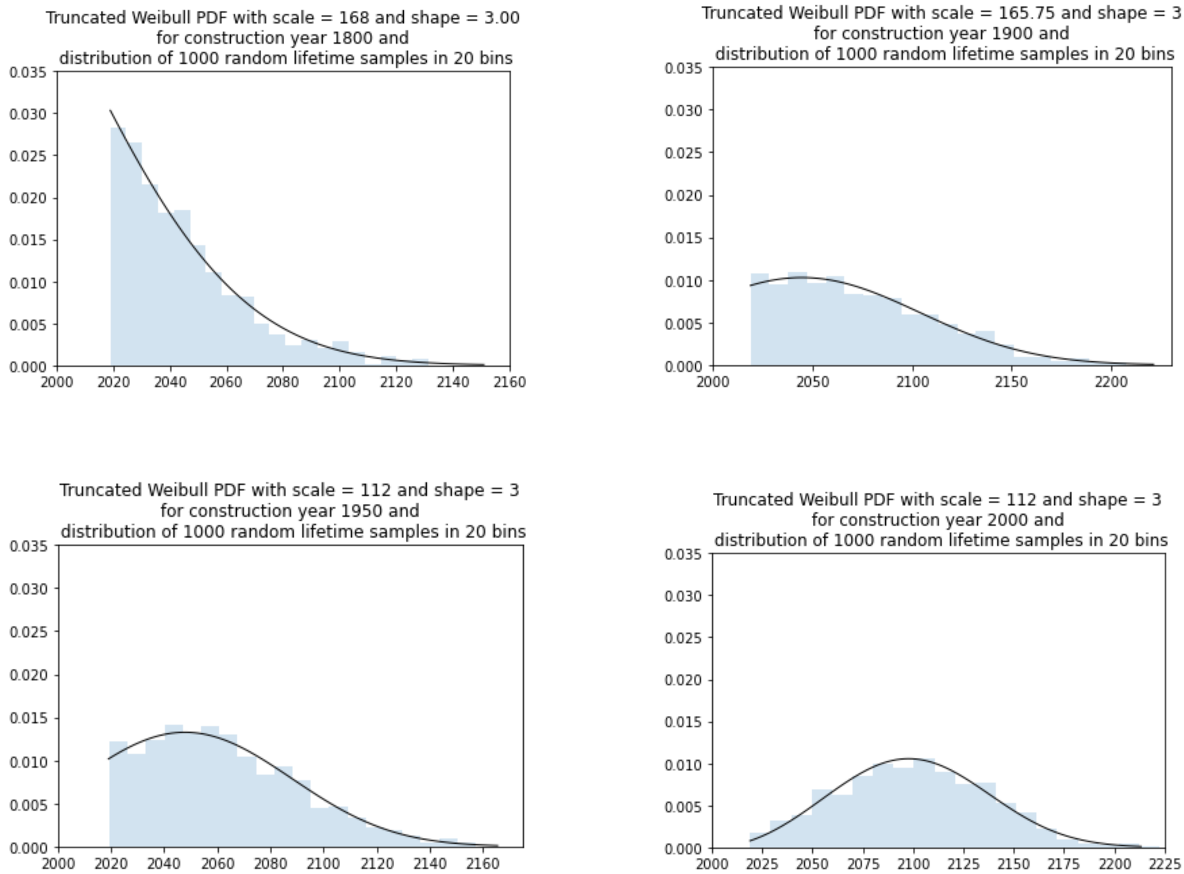

Figure J.2: Truncated Weibull PDF and correlating distribution of 1000 random samples for non-residential buildings. These are four examples for buildings with construction years 1800, 1900, 1950 and 2000, applying the values stated in Table 3.2.

K

Normal Distribution Used for Renovation Cycle Length Sampling and the Correlating Distribution of Random Samples

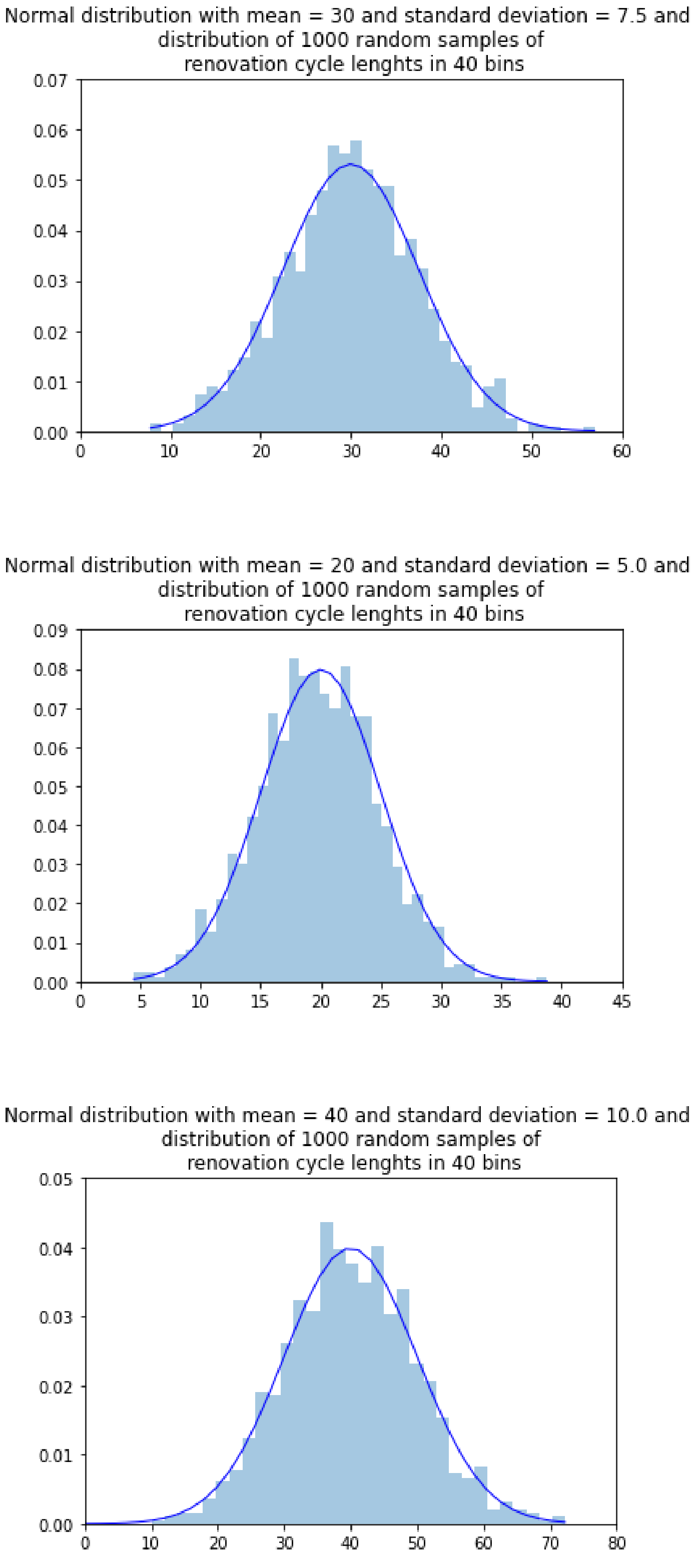

Figure K.1: Normal distribution and correlating distribution of 1000 random samples for the renovation cycle length of residential buildings (top), non-residential buildings (middle) and garages (bottom).

L

Weibull Distribution Used for Lifetime Sampling of Replacement Buildings and the Correlating Distribution of Random Samples

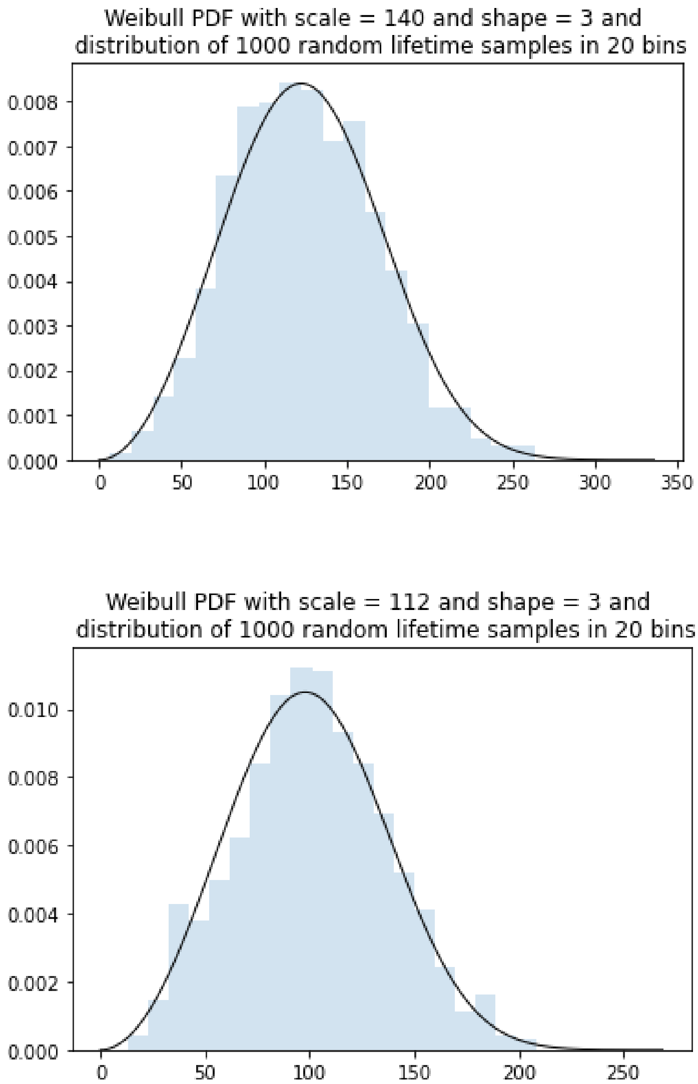

Figure L.1: Weibull PDF and correlating distribution of 1000 random samples for the lifetime of residential buildings and garages (top) and non-residential buildings (bottom).

M

Comparative Analysis of Different Construction Year Allocation Approaches for Residential Buildings

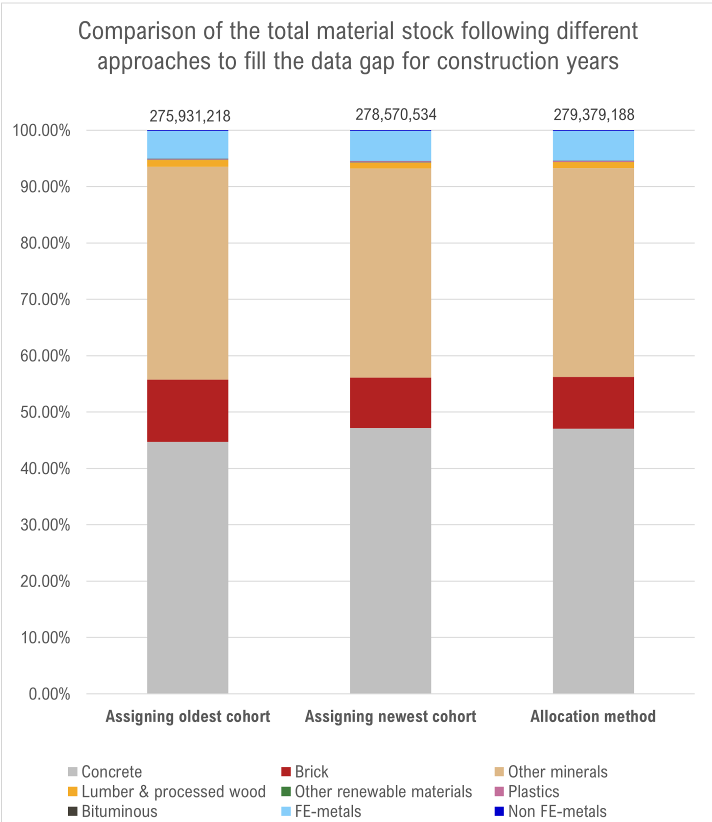

Figure M.1: Comparison between three approaches on filling the data gap for construction years of residential buildings and the respective results. The values on top of the columns show the absolute material mass in [t].

N

Spatial Distribution of Buildings by Function Group

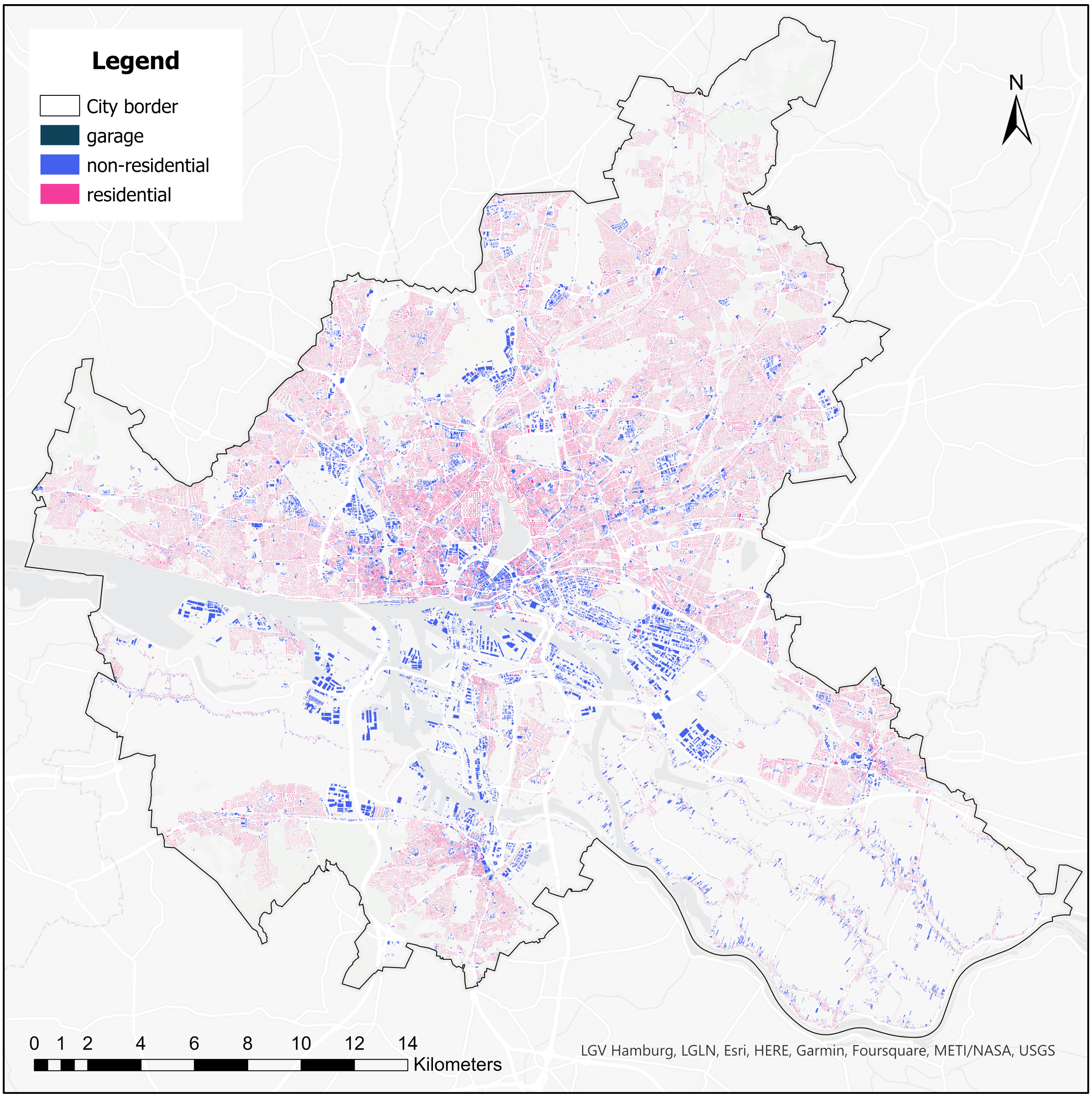

Figure N.1: Spatial distribution of buildings in Hamburg by function group.

0

Spatial Distribution of SFH and MFH

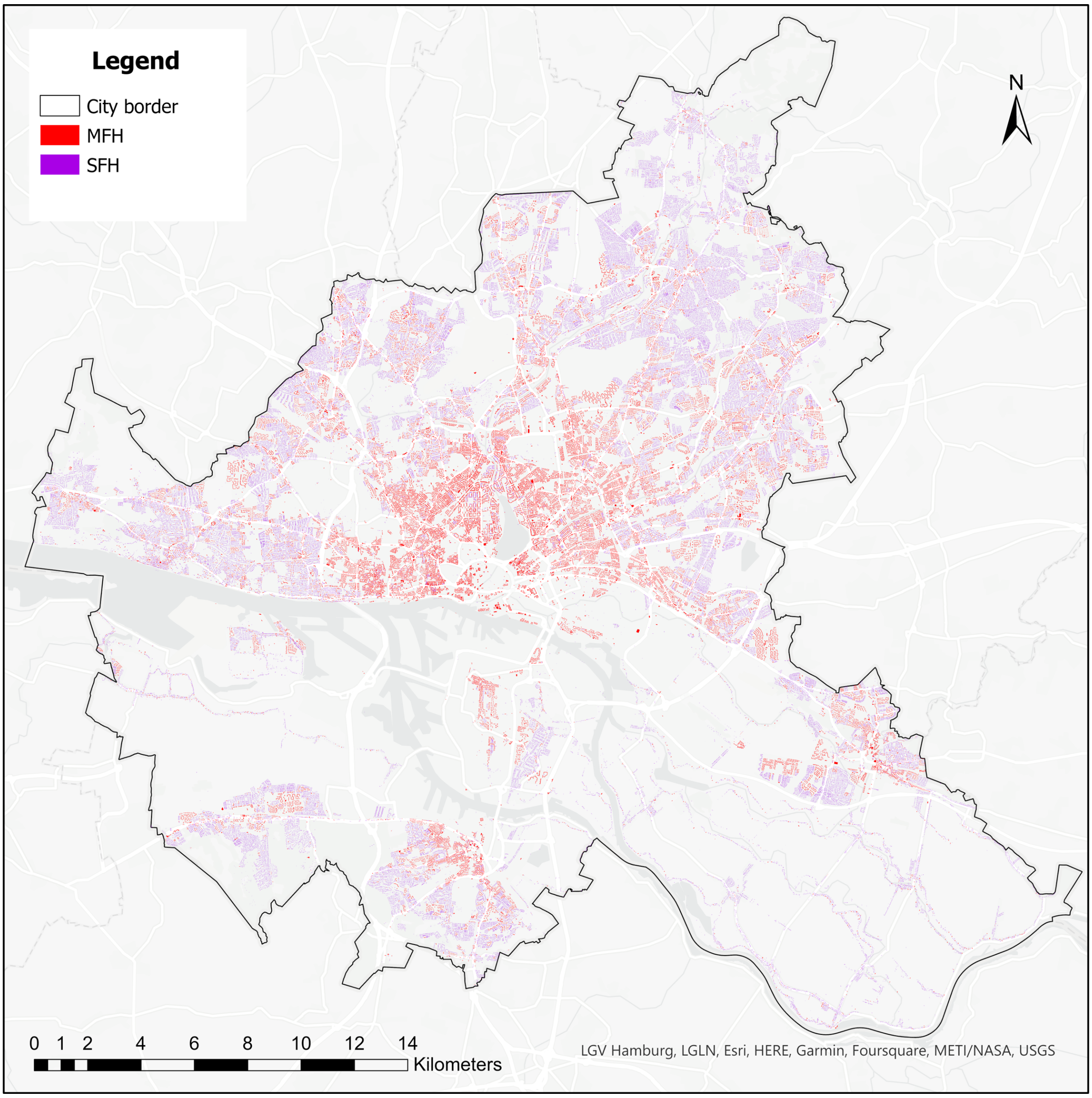

Figure O.1: Spatial distribution of SFH and MFH in Hamburg.

P

Share of Function Groups in the Number of Renovated and Demolished Buildings per Year

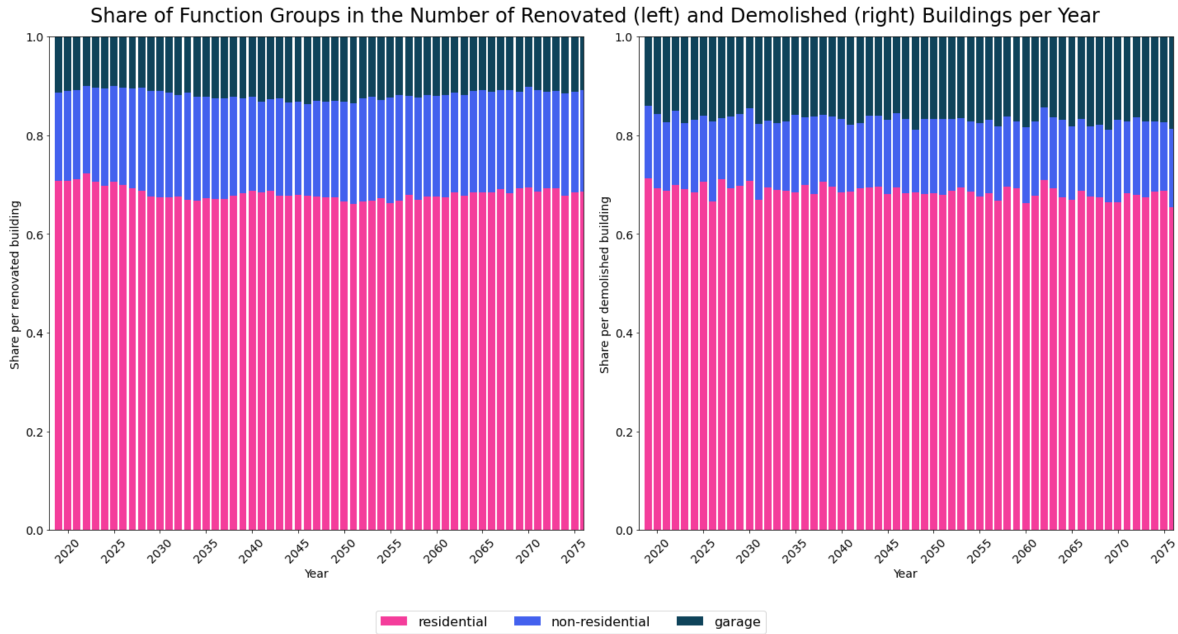

Figure P.1: Share of function groups in the number of renovated (left) and demolished (right) buildings per year until 2075.

Q

Total Inflows and Outflows for Non-Residential Buildings

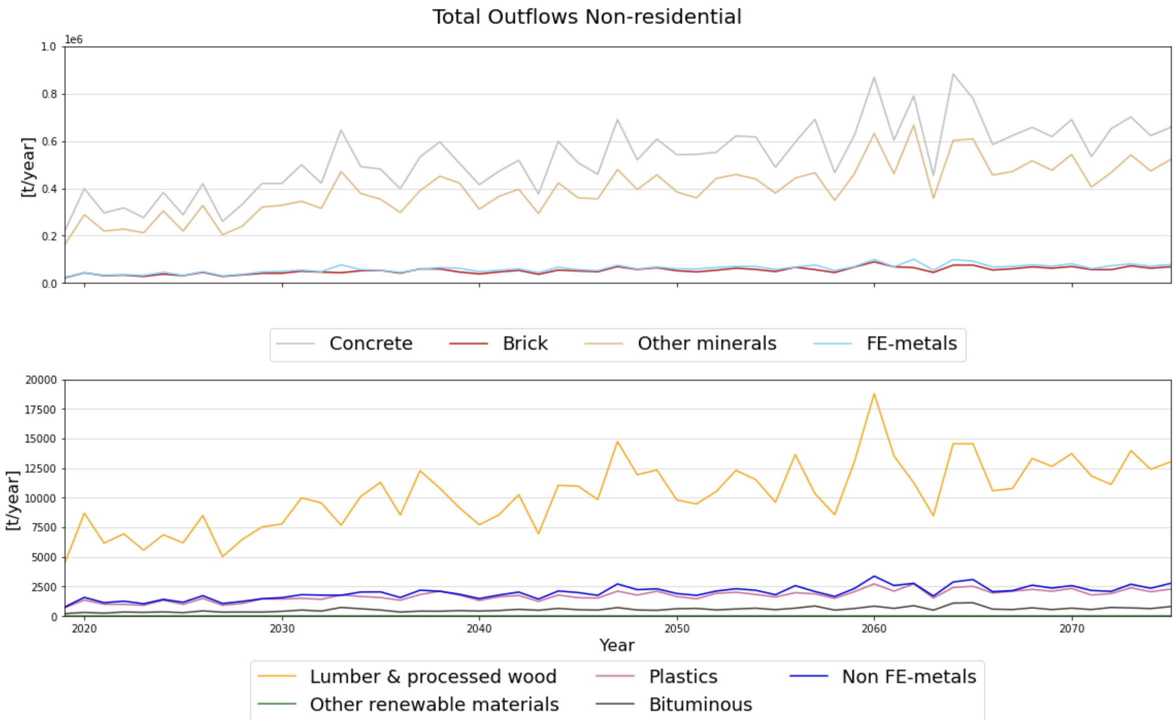

Figure Q.1: Total outflows for non-residential buildings until 2075 in [t/year]. Top: Bulk materials. Bottom: Non-bulk materials.

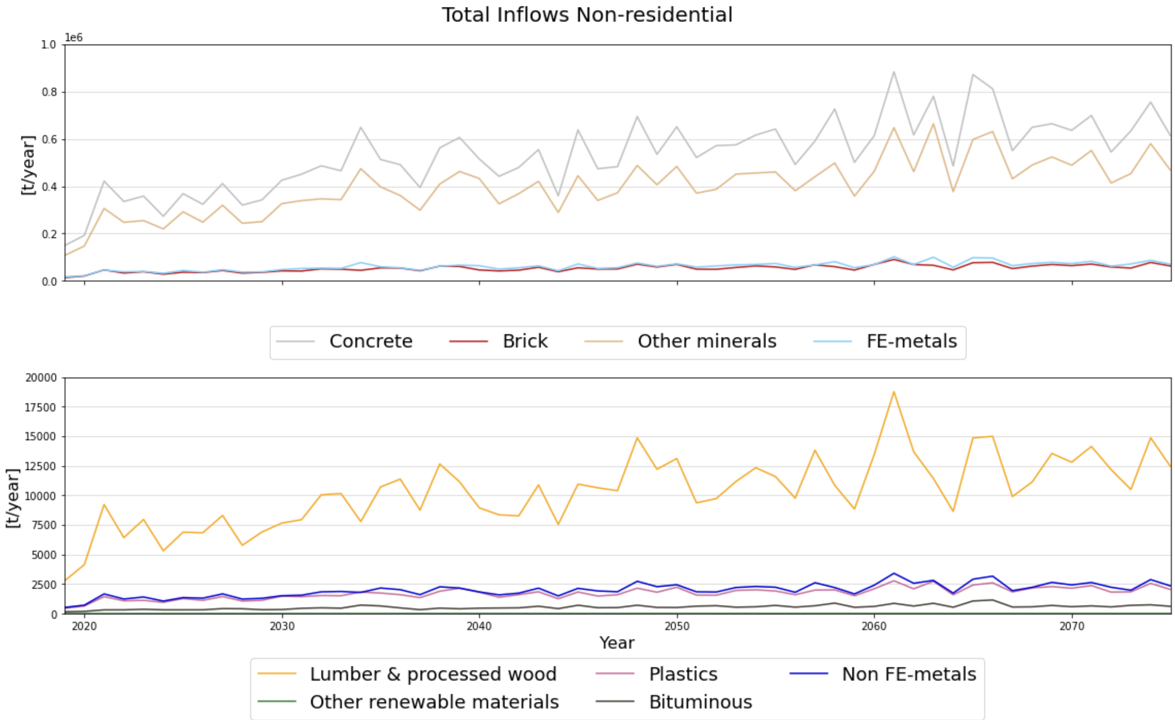

Figure Q.2: Total inflows for non-residential buildings until 2075 in [t/year]. Top: Bulk materials. Bottom: Non-bulk materials.

R

Spatial distribution of Buildings to be Demolished by 2030

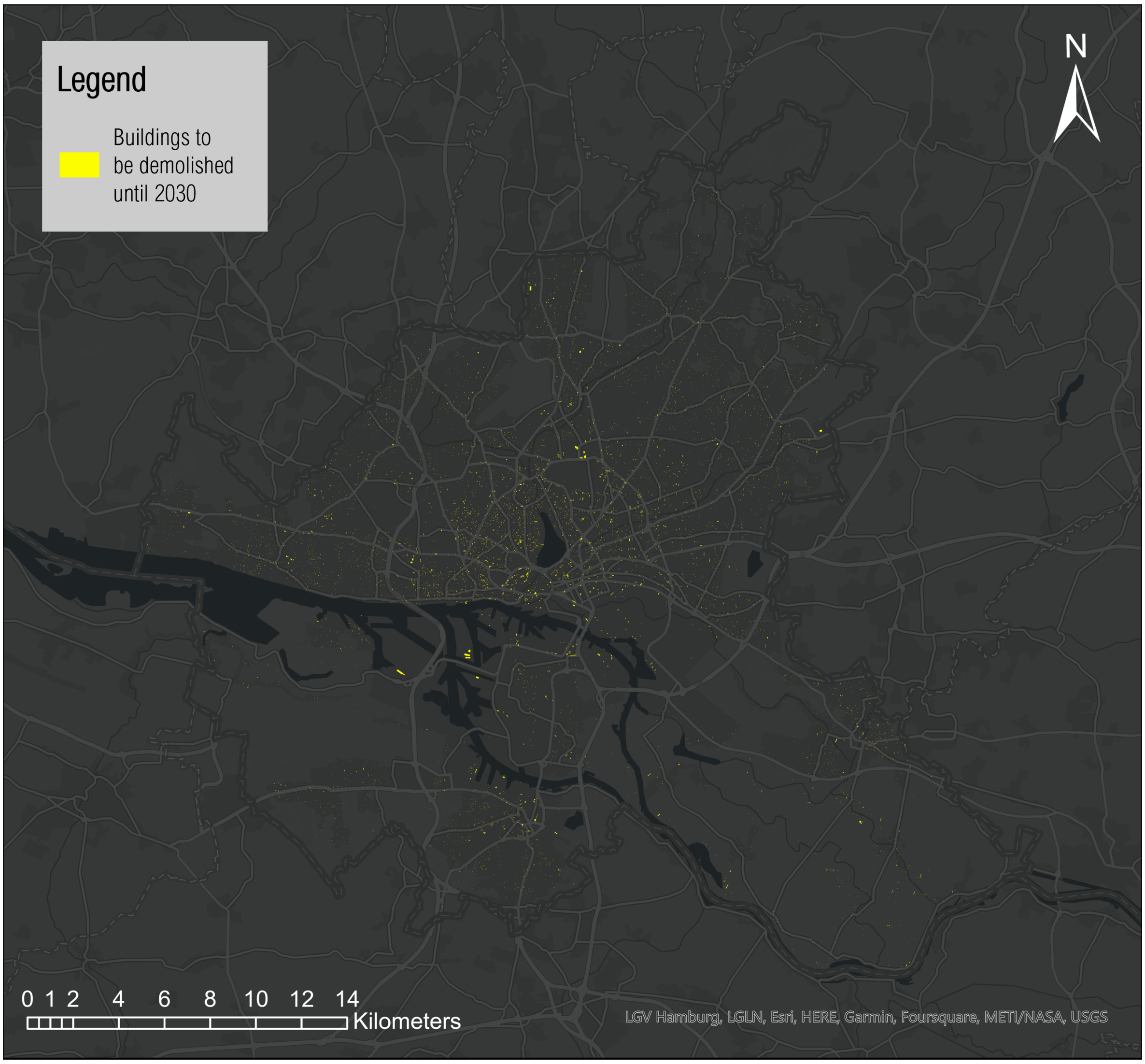

Figure R.1: Locations of buildings to be demolished by 2030.

S

Spatial distribution of Concrete and Brick Density

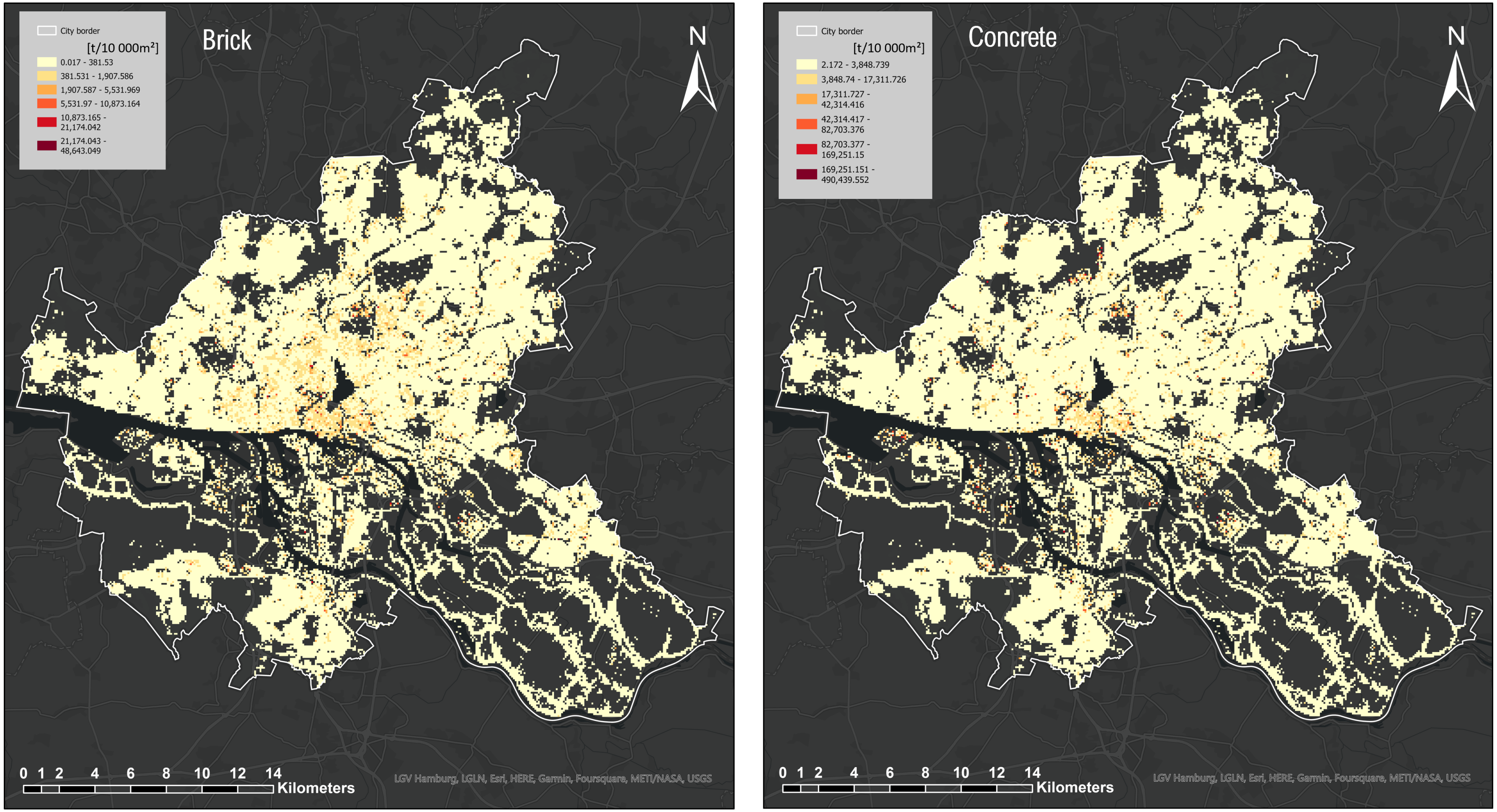

Figure S.1: Spatial distribution of concrete and brick density