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MASTER THESIS:

QUANTIFICATION OF MATERIALS IN BUILDING STOCKS AND MATERIAL FLOWS BY 2040 IN HAMBURG

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ABSTRACT

According to Michiel Schwartz in his work "*A Sustainist Lexicon: seven entries to recats the future*", circular-approaches -to the city, the economy, design- extend well beyond just limiting environmental impacts, but taking on a more systemic, cyclical view of how physical, biological processes, together with human interactions, give rise to sustainable living environments.

The concept of circular economy manifests itself as key when applied in large metropolitan areas, as these are the main representation of the human way of life nowadays. When it comes to determining resource flows in a given country or area, large metropolitan areas are represented as huge sinks or consumers where goods encounter their final use. For some years now, and above all due to the current environmental, social and geopolitical context, it has caused a change of mentality in modern societies towards with a constant questioning of the existing paradigms. The reality is categorical, today more than ever, cities must go from being sinks, to become living environments in which waste generates can go on to have a new useful life for the same or different service.

Traditionally, the construction sector has always been one of the main consumers of material resources for all countries around the world. The recent trend in the economy towards more circular and efficient models, as well as the situation of uncertainty at world level, have highlighted the need for more efficient management of the stock of material present in cities, as well as the waste derived from this activity. The need to recirculate these materials highlights the scarce current information on the total material present in a given are, along with the difficulties in determining methods to quantify it.

The city of Hamburg, as the second largest city in Germany, is a clear example of the need to implement structural changes in the construction sector in order to promote a rational and responsible use of material resources. To this end, three main lines of action are identified and discussed in this Thesis. First of all, it is necessary to determine adequate models in order to quantify the total of existing material in the city. Secondly, to identify social, economic and constructive trends, past and present, so that it is possible to obtain a model capable of objectively predicting waste material flows in the future. And finally, the evaluation of the current status of use and trade of recycled materials in order to improve mechanisms of exchange and trade, and therefore encourage their use.

1 INTRODUCTION

According to the latest report from the European Commission for the Environment on Construction and Demolition Waste (CDW) this issue represents approximately 25%-30% of the total flow of waste material in the European Union (*Construction and demolition waste - Environment - European Commission*, n. d.). The recycling rate for CDW was on average intended to be increased to 70% of the waste produced until 2020, but unfortunately this goal is far from being achieved. It should be noted that this fact is particularly relevant in the case of Germany, which represents approximately 25% of the available living land, and that, due to its importance at both the population and economic levels, it will have a more than significant impact on the environmental development of the EU (*Construction and demolition waste - Environment - European Commission*, n. d.). It is also important to highlight the importance of the city of Hamburg due to the size of its metropolitan area, which ranks as the twelfth largest in the EU in terms of population according to Eurostat data. The main objective of this thesis is to enable circularity in the built environment by increasing the reused and recycled materials in new construction. In order to achieve this, quality of materials, end user trust, creation of a market for secondary materials and prediction of waste material flows should be addressed. On the other hand, the first point in the entire chain is to identify the secondary raw materials prior to demolition. In order to achieve the points described above a study of the current state of the recycling rates particularly in Hamburg and the market for recycled building materials has been carried out together with an evaluation of the different usage habits of present and potential customers. Along with this, the creation of a database with the quantities of materials and the information on buildings can be useful to predict the expected amount of materials in the building. Specifically, a database that involves:

- The building data (age, floor size, etc) based on classification systems.
- Ranking of buildings that are at a low or high demolition risk based on urban planning.
- The amount of materials in the building.

As regards the market for recycled products in Europe, consisting mainly in mineral based materials, an upward trend has been observed in the number of platforms for commercial exchange arising from various initiatives, either public or private, or a combination of both. The vast majority of the sources consulted indicate that the main barriers faced by recycled construction products are: higher cost, unconsolidated standardisation and reduced availability and accessibility. With a view to eliminating this type of impediment, it is concluded that the most useful measures would be, on the one hand, to improve the mechanisms for exchanging these materials so as to increase their supply and accessibility to a greater number of potential users.

In order to create databases, it is necessary to consider the current stock of material present in the city of Hamburg both for residential and non-residential buildings, observe its trend based on available data and evaluate the trend in waste material in future years based on various considerations. A number of bottom-up approaches have been applied, combined and compared for this purpose, divided mainly into those based on the age group of the different buildings as well as the type of use of the different buildings.

The results of the different methodologies have first been compared in qualitative terms, with differences being observed between those in which the input is the floor space in absolute terms. These differences are due, in both the cases of residential and non-residential stock, to the different construction techniques according to the region of study. In general, in cases where the input is the volume of construction based on building permits the differences found have been practically inexistent. Finally, these differences have also been evaluated on the basis of the *ANOVA* statistical test so that it is possible to corroborate the qualitative observations of the results.

This thesis also focuses on predicting the flows of waste material generated from construction, renovation and demolition activity in the city of Hamburg in the 2040-time horizon. To this end, the decision was taken to create a model that represents construction activity as faithfully as possible on the basis of socio-economic indicators.

2 BACKGROUND

2.1 Current status of the housing stock in the European Union

In 2016, the housing stock in the European Union is comprised of a total of 25 billion square meters of available living floor space, of which three quarters fall into the category of residential buildings (Artola et al., n. d., p.15).

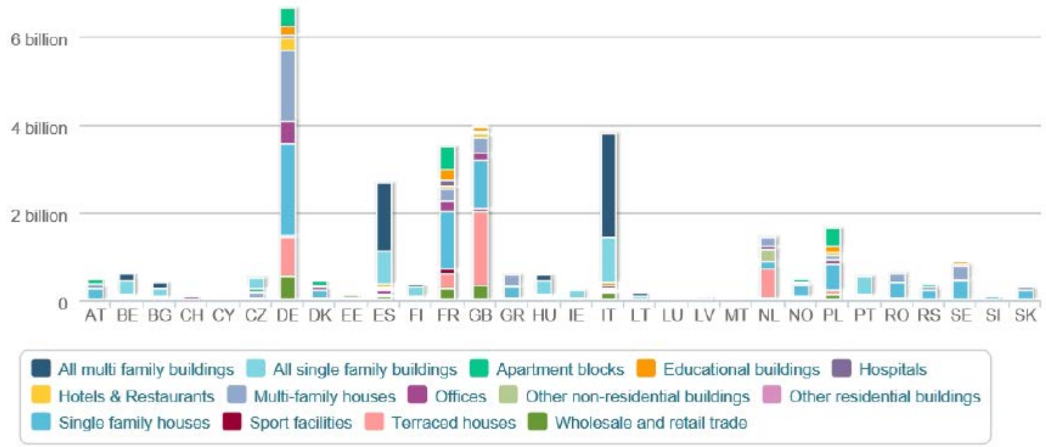


Illustration 1. Building stock floor area (m^2) per building type per Member State

Note. Reprinted from (Artola, et al., n. d., p.15)

As can be seen in Illustration 1, an enormous percentage of the residential stock is made up of multi-family houses and single-family houses. The case of Germany is noteworthy, exceeding 6 billion square meters and representing 25% of the total available living floor space in the European Union.

Commonly throughout the EU, high percentage of these buildings is currently in need of renovation or demolition. Of the total housing stock, 40% was built before 1960, and 60% before 1990 (*Europe's Buildings under the Microscope*, n. d., p. 9). Although some of them are considered as historical buildings and therefore are protected and maintained, the rest have an average life expectancy around 80 years, especially 77 years for the particular case of Germany (Ortlepp et al., 2016, p. 38). Accordingly, the average time period for renovating buildings in Germany is estimated between 30 and 50 years after construction (*Wie lange hält ein Haus* | *Die Lebensdauer einer Immobilie* | *Baumensch*, n. d.). In the light of these data and based on average life expectancy data for residential housing, a significant waste flow form renovation and demolition activities in the EU can be assumed until 2050.

For the particular case of the city of Hamburg, based on data on residential buildings by age group provided by *Statistisches Bundesamnt* in 2002, nearly 491.000 residential buildings in the city, more than 50% of the total stock, were built in the period between 1949 and 1978 (see APPENDIX A). In view of the data on the average life expectancy of housing in Germany, this information will be enormously important when determining the flows of waste material derived from demolition activity once buildings constructed in the aforementioned period are demolished.

2.2 Construction and demolition waste & recycling

Construction and demolition waste (CDW) is, in almost every country in Europe, the most voluminous waste stream generated in the EU, representing approximately 25%-30% (see APPENDIX B) of all waste generated and consists of numerous materials, including concrete, bricks, gypsum, wood, glass, metals, plastic, solvents, asbestos and excavated soil (*Construction and demolition waste - Environment - European Commission*, n. d.).

CDW is currently one of the main lines of action in the EU. In recent years there has been a great potential for recycling, since many of the components used in construction have a high resource value (*Construction and demolition waste - Environment - European Commission*, n. d.). The main objective of the Waste Framework Directive (2008/98/EC) is to encourage the transition to a sustainable society with a high degree of resource efficiency, promoting a minimum of 70% recycling by weight of non-hazardous waste by 2020 (*Construction and demolition waste - Environment - European Commission*, n. d.).

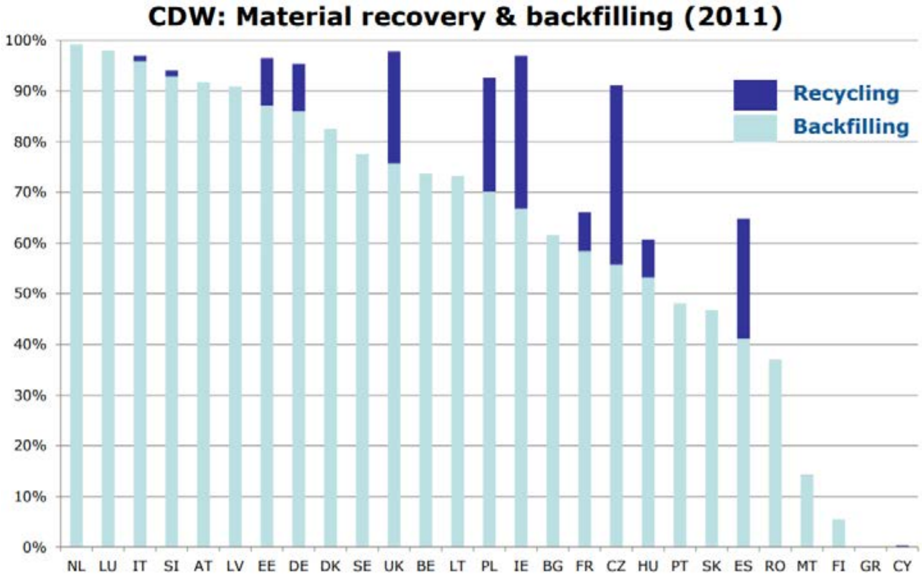


Illustration 2. CDW in the EU: Material recovery and backfilling (2011)

Note. Reprinted from (*Construction and demolition waste - Environment - European Commission*, n. d.)

Despite the enormous potential of reuse and recycling, construction and demolition waste not properly managed in the EU, as shown in Illustration 2. Backfilling dominates as a management process. Particularly in Germany, there is an annual recycling rate of 10%.

2.2.1 Construction and demolition waste & recycling in Hamburg

In this section, the generation of waste derived from construction and demolition activities will be evaluated for the particular case of the city of Hamburg. Firstly, for each of the most significant groups of materials that make up the total stock, the waste registered in previous years will be displayed, as well as the official predictions for future years. This data is derived from*“Gemeinsamer Abfallwirtschaftsplan für Bau- und Abbruchabfälle von Hamburg und Schleswig-Holstein (2019)“*.

In Illustration 3 it is possible to observe the trend in CDW generation, both hazardous and non-hazardous waste, between 2000 and 2015. Here, it is possible to identify a clear decrease in waste generation between 2000 and 2005, followed by a subsequent stabilization of the annual value around 200 million tonnes of construction and demolition waste.

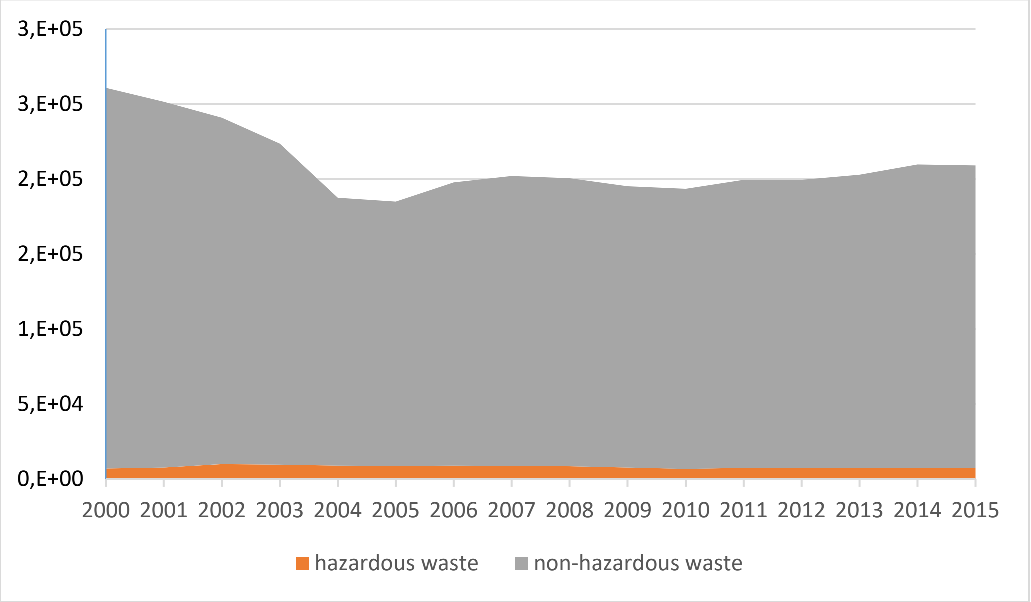


Illustration 3. Annual amount of waste in derived from the construction and demolition activity (1.000 tones) (*Material and Energy Flows*, n. d.)

Table 1. CDW in the city of Hamburg and Schleswig-Holstein (2016)

Waste type	**Amount 2016 (tMg)**
Mineral rubble	2706
Wood	240
Soil and stones	4599
Metals and plastics	228
Gypsum based building materials	50
Insulation materials	0,5
Quantity-relevant hazardous construction waste	358
TOTAL CONSTRUCTION/DEMOLITION WASTE	**8181,5**

Note. Reprinted from Gemeinsamer Abfallwirtschaftsplan für Bau- und Abbruchabfälle von Hamburg und Schleswig-Holstein 2019, p. 33

Table 1 shows the different amounts of waste derived from construction and demolition activities for the year 2016. The following shows the different quantities of waste material obtained for Hamburg and Schleswig-Holstein in the period between 2013 and 2016. In turn, predictions of waste material between the years 2020 and 2030 will be shown.

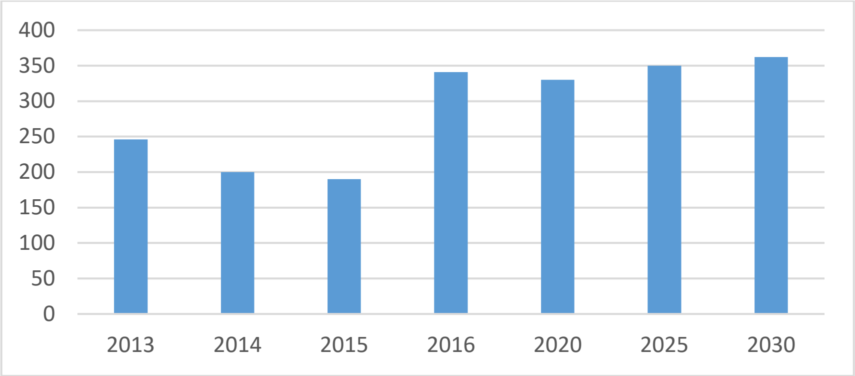


Illustration 4. Waste mass of concrete in Hamburg and Schleswig-Holstein from 2013 to 2016 and development trend until 2030

Note. Reprinted from (Gemeinsamer Abfallwirtschaftsplan für Bau- und Abbruchabfälle von Hamburg und Schleswig-Holstein, 2019, p. 36)

Illustration 4 and 5 show the respective amount of concrete and ceramic waste. Approximately all of this waste material (99% by mass, 2016) is recycled in this area (*Gemeinsamer Abfallwirtschaftsplan für Bau- und Abbruchabfälle von Hamburg und Schleswig-Holstein (2019)*, p. 36). Traditionally, mixture of concrete, bricks, tiles and other ceramic materials were used in Hamburg and Schleswig-Holstein largely on access routes to wind turbines (*Gemeinsamer Abfallwirtschaftsplan für Bau- und Abbruchabfälle von Hamburg und Schleswig-Holstein (2019)*, p. 36).

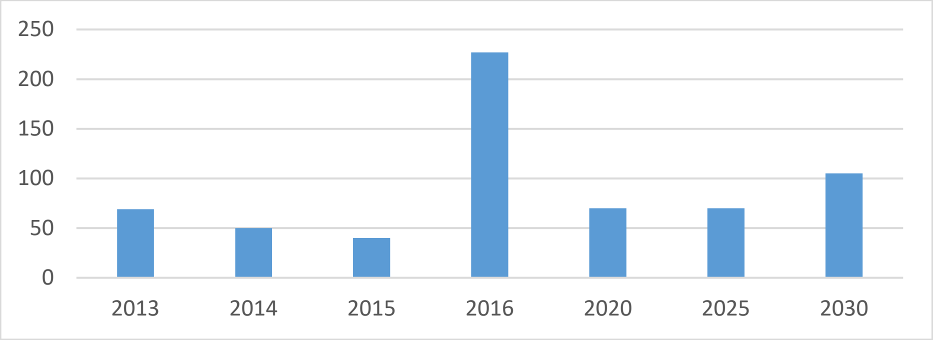


Illustration 5. Waste concrete mass of ceramics and bricks in Hamburg and Schleswig-Holstein from 2013 to 2016 and development trend until 2030

Note. Reprinted from Gemeinsamer Abfallwirtschaftsplan für Bau- und Abbruchabfälle von Hamburg und Schleswig-Holstein 2019, p. 36

In Illustration 6 it is possible to observe the quantities of wood-based materials that were disposed within the indicated period, along with the future predictions. In Schleswig-Holstein, this waste has increased from approximately 154 tMg in 2013 to 182 tMg in 2016. In Hamburg, the resulting quantities have increased in the same period and reached 57 tMg. Regarding the predictions for the city of Hamburg, there might be a slight increase, from 57 tMg in 2016, to 63 tMg in 2030 from (Gemeinsamer Abfallwirtschaftsplan für Bau- und Abbruchabfälle von Hamburg und Schleswig-Holstein (2019), p. 38). It should be noted that construction and demolition activities are subject to material recycling in the wood-based and cellular material industry or energy recovery. Because of this, almost all the wood fraction will be recycled (Gemeinsamer Abfallwirtschaftsplan für Bau- und Abbruchabfälle von Hamburg und Schleswig-Holstein (2019), p. 38).

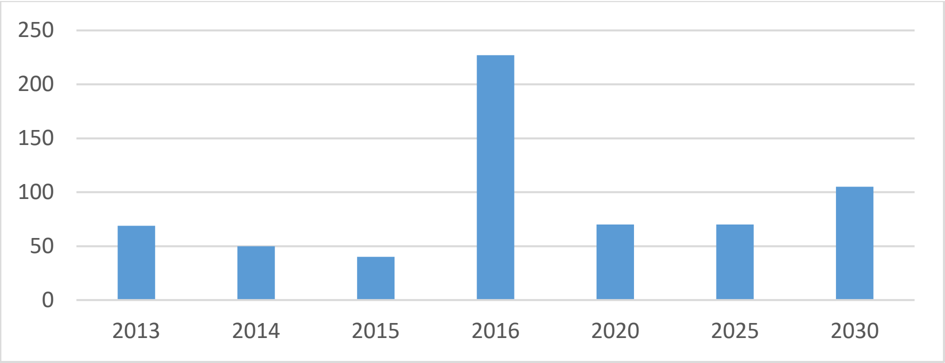


Illustration 6. Waste mass of wood in Hamburg and Schleswig-Holstein from 2013 to 2016 and development trend until 2030

Note. Reprinted from Gemeinsamer Abfallwirtschaftsplan für Bau- und Abbruchabfälle von Hamburg und Schleswig-Holstein, 2019, p. 37

Excavation of construction pits for structures, large projects in civil engineering and infrastructures, provide the most relevant waste stream from construction and demolition waste. As shown in Illustration 7, both in Hamburg and Schleswig-Holstein, the total volumes increased by 2015, but reduced to around 4.599 tMg in 2016, reaching the values of 2013. In relation to the predictions for the period between 2020 and 2030, a continuous increase in this type of waste is expected (Gemeinsamer Abfallwirtschaftsplan für Bau- und Abbruchabfälle von Hamburg und Schleswig-Holstein (2019), p. 39). This type of material is used in the filling of excavations. In 2016, approximately 56% mass was recycled over this disposal route. Around 30% mass was recycled in treatment plants, the rest was disposed in landfills from (Gemeinsamer Abfallwirtschaftsplan für Bau- und Abbruchabfälle von Hamburg und Schleswig-Holstein (2019), p. 39).

In the case of metallic materials and plastics, there are no separate data for Hamburg and Schleswig-Holstein, so it is suggested that most probably, quantities incurred in Hamburg were treated in Schleswig-Holstein treatment plants (Gemeinsamer Abfallwirtschaftsplan für Bau- und Abbruchabfälle von Hamburg und Schleswig-Holstein (2019), p. 39). The metals that are found in a higher concentration are mainly iron and steel (e.g. steel girders, reinforced concrete), copper (e.g. lines, cables) and aluminum (e.g. window frames, facades). Usually, most of these metallic materials can be completely recycled (Gemeinsamer Abfallwirtschaftsplan für Bau- und Abbruchabfälle von Hamburg und Schleswig-Holstein (2019), p. 39). On the other hand, plastics can be found in construction in the form of PVC products, such as window frames and floor coverings. Furthermore, high recycling rates can be achieved if these materials are collected separately Gemeinsamer Abfallwirtschaftsplan für Bau- und Abbruchabfälle von Hamburg und Schleswig-Holstein (2019), n. d., p. 39.

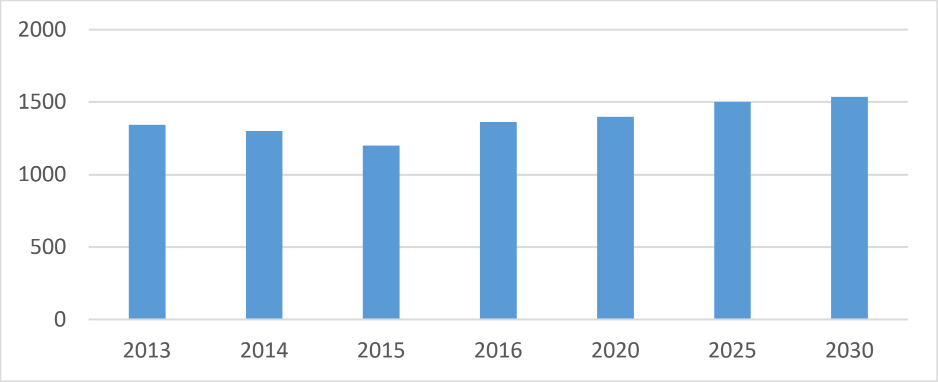


Illustration 7. Soil and stones-Volume in Hamburg and Schleswig-Holstein from 2013 to 2016 and development trend until 2030

Note. Reprinted from Gemeinsamer Abfallwirtschaftsplan für Bau- und Abbruchabfälle von Hamburg und Schleswig-Holstein, 2019, s. f., p. 39

As Illustration 8 shows, both in Hamburg and in Schleswig-Holstein the amount of building materials on gypsum basis has risen continuously since 2013. It totaled approximately 4 tMg in 2016 in the case of Hamburg. Although gypsum based building materials are technically easy to recycle and RC gypsum has similar quality to natural gypsum, most of the gypsum-containing waste is currently disposed in landfills in Germany (Gemeinsamer Abfallwirtschaftsplan für Bau- und Abbruchabfälle von Hamburg und Schleswig-Holstein (2019), s. f., p. 40). In 2016, around 31% of the total materials containing plaster was recycled (Gemeinsamer Abfallwirtschaftsplan für Bau- und Abbruchabfälle von Hamburg und Schleswig-Holstein (2019), p. 40).

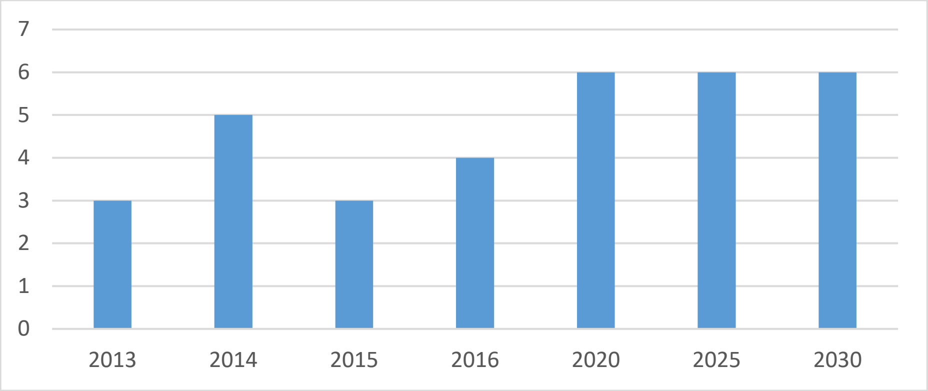


Illustration 8. Waste mass of gypsum-based materials in Hamburg and Schleswig-Holstein from 2013 to 2016 and development trend until 2030

Note. Reprinted from Gemeinsamer Abfallwirtschaftsplan für Bau- und Abbruchabfälle von Hamburg und Schleswig-Holstein, 2019, p. 41

2.2.2 Waste management and circular material flow data

2.3 Market of recycled materials

The construction industry is currently pursuing ways to mitigate its environmental impact, since global economy, driven by governments and various multilateral agencies, tends towards value-generating activities based on sustainable policies. Construction waste causes significant damage, so increasing the recycling rate of these materials would generate a significant reduction in environmental impact. As a lobbyist of European recycling of building materials European quality Association for Recycling e. V. (EQAR) strives in order to reach quality-controlled recycled building materials in the sense of the environmental and resources protection (*European Quality Association for Recycling e.V. (EQAR)- Info-Center - European Market of recycled building materials*, n. d.).

In recent years, both at European and global level, there have been a number of public and private initiatives aimed at promoting platforms for the use of recycled materials. A clear example of this type of initiative is *restado*, a private initiative with scope in Germany, Switzerland and Austria (*restado - Marketplace for the reuse of construction material* | *European Circular Economy Stakeholder Platform*, n. d). This platform created in March 2017, promotes a marketplace for the commercial exchange of construction materials from demolition activity, with demand in new construction projects and making the resource suitable for both private and professional buyers (*restado - Marketplace for the reuse of construction material* | *European Circular Economy Stakeholder Platform*, n. d.). The majority of the building materials are leftovers from the dismantling or over-orders of commercial and private construction sites. Similar initiatives have taken place in other European countries. Some of these will be shown in Table 2.

Table 2. Some European initiatives for the promotion of marketplaces for reusable building materials

Enviromate	UK
“One planet handle with care” Circular Building Platform	Netherlands
Excess Materials Exchange	Netherlands
Agencia de Residuos de Cataluña “ZICLA”	Spain

It should be noted that the examples shown in Table 2 have been selected in order to form a sample of the different types of initiatives mentioned above. In the first case, the British platform *Enviromate* is a private initiative aimed at providing a forum for exchange (*Enviromate* | *Free Leftover Building Materials Marketplace*, n. d.). Similarly there is the Dutch initiative *Excess Materials Exchange* (*Excess Materials Exchange*, n. d.). These platforms make up other similar private initiatives in other European countries.

As another type of initiative promoted by a supranational organization (*UN* for Environment), “One planet handle with care” *Circular Building Platform (Digital Reuse Marketplace)* is presented. It is part of one of the six action frameworks of the UN in order to promote circular economy in a time horizon set at 2022 (*Digital Reuse Marketplace*, 2019). In this case, the initiative has been set up in the Netherlands but the framework for its action will be extended to Europe and several Central Asian countries (*Digital Reuse Marketplace*, 2019).

The importance given in recent years to the promotion and understanding of markets for recycled products is evident from the perspective of the relevance of the interactions between these and the production of virgin material for the implementation and evaluation of different material recycling policies (Söderholm & Ekvall, 2020). The success of recycling depends entirely on whether or not it makes economic sense, in order to build demand for recycled materials, government and business must reinvent both their internal mechanisms and the relationship between them (Biddle, 1993, p. 21). The recycling rate for construction and demolition waste was on average intended to be increased to 70% of the waste produced until 2020 in the 25 EU countries, as stated above, this goal is far from being achieved in the proposed time horizon in the vast majority of countries (*European Quality Association for Recycling e.V. (EQAR)- Info-Center - European Market of recycled building materials*, n. d.). In some countries such as Austria, Denmark, Germany and the Netherlands a recycling rate of more than 70% was stated, whereas this potential is still available in the remaining European states (*European Quality Association for Recycling e.V. (EQAR)- Info-Center - European Market of recycled building materials*, n. d.). The waste produced in European construction sector consists predominantly of mineral waste, providing huge potential in order to produce high-quality construction products in the sense of a closed cycle (*European Quality Association for Recycling e.V. (EQAR)- Info-Center - European Market of recycled building materials*, n. d.).

The market for recycled materials has traditionally proved to be an industrial buyer's market for all recyclable commodities, this translates into an ability for these users to choose a supplier and thus keep the price down (Biddle, 1993, p. 21). Because of this, producers of recycled material have in most cases ended up actively competing. In many cases, recycled materials producers must also compete with virgin raw materials (Biddle, 1993, p. 21). A greater demand for these types of materials would generate the need for an improvement in both their quality and availability, allowing for economies of scale in pursuit of productivity (Biddle, 1993, p. 21). By means of technological test criteria a high quality and excellent suitability of the materials can be obtained, being able to achieve even greater cost-effectiveness than primary building materials through modern production plants (*European Quality Association for Recycling e.V. (EQAR)- Info-Center - European Market of recycled building materials*, n. d.).

Traditionally, when implementing mechanisms and platforms to promote trade in recycled materials, three main issues have been encountered according to Biddle (1993):

- Higher cost of recyclable construction materials in comparison to primary products.
- Lower quality along with a poorer quality control.
- Less availability and capacity to meet instant necessities in scale economies.

It should be noted that these reasons for reluctance to purchase recycled building materials were first identified in 1993, and they have been maintained to date in spite of the efforts made in order to improve both the production processes and the mechanisms of trade.

According to the European Environment Agency (2017) the main issues regarding barriers to the uptake of circular economy are:

- Price competition with virgin materials.
- Confidence in quality and structural properties of secondary materials due to standardized warranties.
- Hazardous substance content due to costly process of removal.
- Lack of sufficient and reliable data on (historical) buildings.
- Time delay.

More recent studies based on surveys carried out among several construction companies have also focused on identifying the various problems that actors involved in the construction process generally encounter when using recycled materials. By watching the results of the survey carried out by Bolden, Abu-Lebdeh and Fini (2013) among 65 participants from 50 companies the state of these markets in the Unitaded States will be presented. The companies surveyed consisted of contractors, engineers, architects and suppliers of concrete, landfills, scrap yards, steel manufacturers, drilling, demolition and recycling companies (Bolden, 2013, p. 22). Regarding the reasons due to which they do not use recycled materials in the construction industry, the cost made up 22%, considering that cost proves more important than benefits when using these materials (Bolden, 2013, p. 21). In turn, companies claimed lack of education to be 13% of this reason, while quality of end products represented 11% of the reason (Bolden, 2013, p. 22). Contamination in terms of reduced performance of the applications made 8% of the reasons, while high cost of separation process, need for permit to certain waste materials and lack of marketing of the recycled product made 7% each of why companies do not use recycled materials (Bolden, 2013, p. 22). In contrast, the reasons why companies do rely on recycled materials for construction activity are: the quality of recycled products by 30%, the cost by 23% and the reduction of landfill waste by 47% (Bolden, 2013, p. 22).

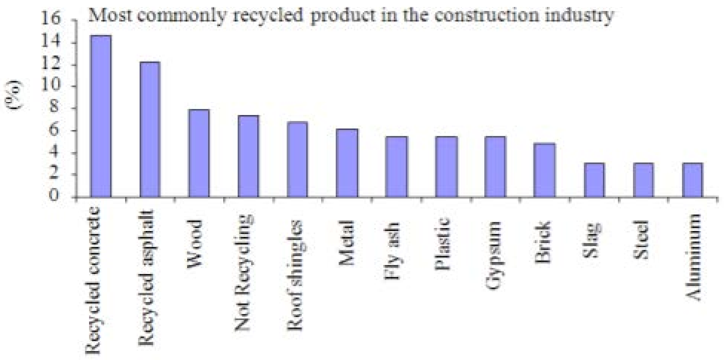


Illustration 9. Most commonly recycled product in the construction industry

Note. Reprinted from Bolden, 2013, p. 22

As a recommendation to reduce these misconceptions and challenges when implementing mechanisms for trade in recycled materials, it is suggested , first of all, to create better documentation for green infrastructure, connecting researches and industry with an overview on the availability for different construction applications (Bolden, 2013, p. 21). Therefore, it is necessary to quantify the material stocks in the built environment in order to maximize utility and value of existing materials. By identifying and listing the origin, quality and age of the materials, it is possible to create useful databases and material passports containing information for further pre-demolition audits (*Construction and Demolition Waste*, n. d.). These databases might be used by experts in order to provide fast recommendations on management routes for construction and waste materials from the perspective of recycling and reduction of consumption of virgin materials.

In turn, secondary materials need to be competitively priced, putting measures such as green taxes into practice (*Construction and Demolition Waste*, n. d.). Furthermore, green procurement campaigns could be implemented in order to create demand for these materials (*Construction and Demolition Waste*, n. d.). Standardization of recycled materials at national level would help to enhance the consideration of these among construction stakeholders

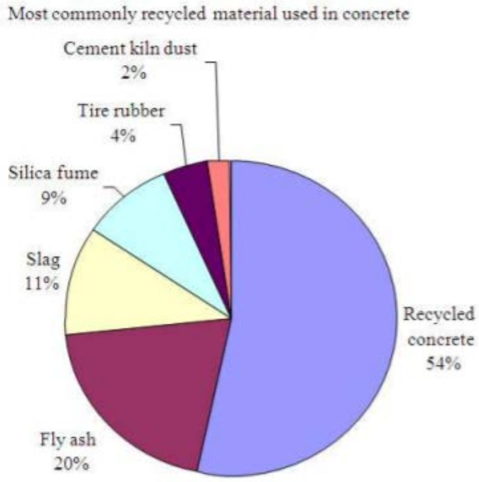


Illustration 10. Most commonly recycled material in concrete

Note. Reprinted from Bolden, 2013, p. 22

Illustration 9 shows the most widely used recycled building materials. It shows a use of 15% for recycled concrete, while materials such as wood, representing 8%, or metals, representing 6%, are used in a lower proportion. The fields where recycled building materials can be applied are wide-ranging, being used not only in concrete and aggregates production or steel and aluminum regeneration, but also, as some new examples, in the production of Plasphalt (use of the grain of plastic instead of sand and gravel to produce asphalt), Timbercrete (uses sandwust as a component to make concrete lighter and cheaper while maintaining robustness in comparison to conventional concrete) or Ferrock (made mostly of waste steel and more durable than concrete) («Top Recycled Building Materials That Are Changing the World», 2019).Illustration 10, shows the most used recycled building materials in concrete, showing that recycled concrete represents the 54% of the total, whilst fly ash and slag represent 20% and 11% respectively.

3 METHODOLOGY

3.1 Scope of the thesis

To integrate circularity in the building sector, the cities must (a) improve the knowledge of building material stocks and flows, and (b) predict the materials expected from demolition activities in the next years. To this direction, in this study various mass scanning, and dynamic input/outputs flows methodologies for materials in buildings have been explored, compared, or/and combined especially in Hamburg study area. It was expected that the amount of materials varies depending on building typologies and classification systems, as present in Hamburg based on existing databases-official data. The output data can be used to create a standardized template for pre-demolition audit, which auditors can use easily and fast to identify and quantify the amount of materials and their quality based on the building type in order to make recommendations for suitable materials management routes before the building demolition.

3.2 Baseline data on housing stock in the city of Hamburg

The analysis of the building structure is based on official data on materials in building stock and construction activity provided by the Federal Statistical Office and the Statistical Office for Hamburg and Schleswig-Holstein. These data mainly reflect the annual variation in Hamburg’s building stock regarding the annual input of living floor space and the gross volume of material input. The data involve residential buildings and apartments in residential and non-residential buildings.

The two main sources of data regarding these matters are:

- “*Statistisches Amt für Hamburg und Schleswig-Holstein: Statistisches Jahrbuch Hamburg*”, which is published annually and contains data on completed apartments among residential buildings divided in multi-family houses (MFH) (more than two apartments per building) and single-family houses (SFH) (one or two apartments per house). These reports provide disaggregated information on floor size per year starting from 1970, the most recent information available is shown on the 2020 report (SEE APPENDIX C).

  Information regarding volume of construction shown in cubic meters is provided from the year 2000 and is separately provided based on the number of building permits.
- Federal Statistical Office “DESTATIS” database, which contains information on several aspects regarding construction activity disaggregated for each of sixteen federal states which conform Germany. This database mainly includes

particularized data on the construction activity for every year, these concerns: building permits, work on existing buildings, completed buildings and demolitions.

- Zensus 2011 database, like the above-mentioned database, it contains information regarding the description of the existing housing stock in the city of Hamburg. It has updated data as of 2011 for the city and its various districts.

The aim of the following sections is to indicate how the above mentioned data were used in combination with factors depending on the building typology (construction year, residential, non-residential, multi or single family house, classification of non-residential building based on the function sector) in order to quantify the material stocks in existing buildings through various methodologies and combinations of them.

3.2.1 Data on available living floor size input

The data represent the total amount of apartments among residential and non-residential buildings in the city and the average size in square meters per apartment in the building stock. Only data from the year 1970 are represented in a disaggregated way. Also, data between 1970 and 2000 are presented in aggregate form over five-year periods. From the year 2000, and until the last 2019, annual data is available. Illustration 11 and 12 present the accumulated stock of living floor space in the city, and the space added annually by construction activities respectively. In Illustration 111 an exponential increase in available floor living space in the city can be seen. This information will be used to make future predictions of waste material flows.

Overall, available living space is calculated by means of the floor space of the previous years and the added floor space. Nevertheless, annual input on available living space is reflected in the documents. In addition, "*Statistisches Jahrbuch Hamburg 2005/2006: Page 93*" provides aggregated data (twenty-year period) on the number of buildings stocks and relative living space depending on the age-group erected starting from 1900 and after (SEE APPENDIX B). It should be noted that there is no information about the amount of single- and multi-family houses. In order to be able to apply later methodologies for accounting the materials the following aspects were considered:

- The available living space is calculated in terms of the average living space per apartment in 2002.
- For the period between 1949 and 1978, a series of assumptions needed to model the housing stock will be made. Especially, in the light of the data from 1970 and after (latest annual release) it was estimated that the amount of living space in

single-family houses in the city of Hamburg represents an average of 20,5 % of the total housing stock. This assumption stems from an observation of the evolution of the single-family housing stock regarding the overall housing stock. In respect thereof, a barely steady proportion is noticed for every year.

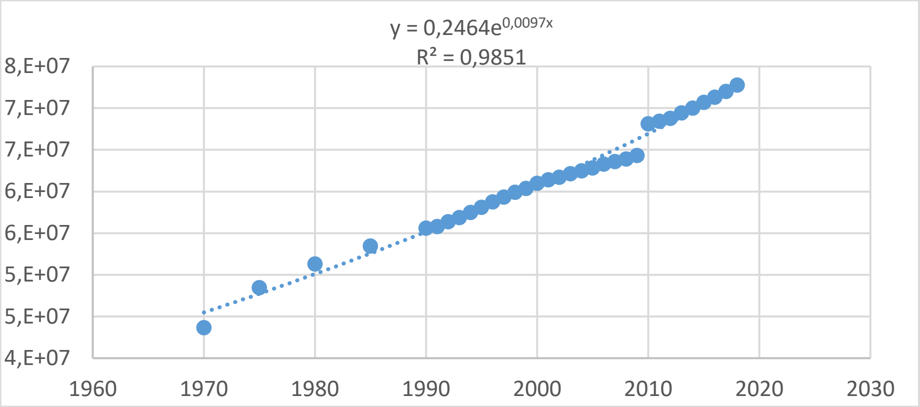


Illustration 11 . Total living floor space in residential and non-residential buildings (sqm)

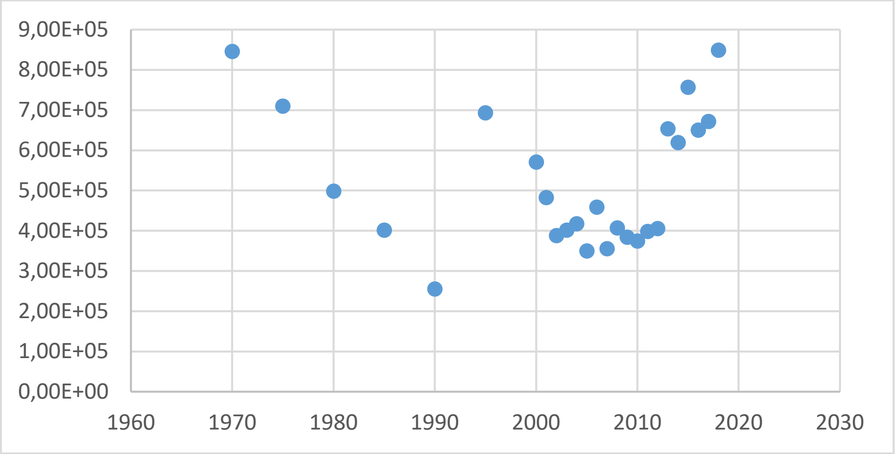


Illustration 12. New-built living space in residential and non-residential buildings

3.2.2 Data on building permits

A building permit is required for the construction, alteration, or demolition in use of a building. The granting of the building permit is subject to the compliance with the planning and building regulation law as well as with other applicable laws (such as environmental laws) (*Planning and Building*, n. d.). From DESTATIS database, it is possible to obtain the total number of building permits issued annual in the city since 2000. This database provides information on residential buildings with their respective annual construction volumes. In addition, for non-residential buildings, it also provides information on four main groups: institutional buildings, office, and administration, agricultural and farm-buildings and non-agricultural farm buildings.

3.2.3 Data on annual volume of construction

From DESTATIS database, it is possible to extract data on the annual construction volume between the years 2000 and 2018 based on annual building permits.

3.3 Calculating existing material stocks of apartments in residential and non-residential buildings

This study attempts to apply, combine, and complete some existing methodologies involving quantification of materials stocks and assessment of material mass flows in Hamburg. Over recent years, a high number of studies have been conducted whereby emphasis has been placed on coefficient-based bottom up approaches as Schiller, Gruhler and Ortlepp (in press) indicated (Ortlepp et al., 2018, p. 164).

Most of the publications regarding the topic of material quantification have considered the domestic building sector rather than the non-domestic sector (Ortlepp et al., 2018, p. 164). The main classification among domestic buildings is applied by size (SFH or MFH) and building typologies regarding the construction year whereas, on the other hand, non-domestic buildings are differentiated according to particular forms of use and age (Bergsdal et al., 2008, p. 28; Ortlepp et al., 2018, p. 165). In spite of the mentioned research, there are some limitations that are commonly identified, such as use of overly generalized coefficients, assumptions, lack of data resulting sometimes in non-accurate assessment of the urban material stock (Ortlepp et al., 2018, p. 166).

The methods considered in the present study involve material quantification in residential and non-residential buildings. The residential buildings are further analyzed separating between large residential buildings or else MFH, and SFH. In addition, in order to evaluate and compare the results accuracy, two types of MCIs are used representing either amount of materials per area or amount of materials per volume. As already mentioned, both the available living area in square meters and the volume of buildings/apartments is available according to the official data in Hamburg. The methodologies applied in this study are those covered in the articles listed below:

- Materials in Germany’s domestic building stock: calculation model and uncertainties (R. Ortlepp, K. Gruhler and G. Schiller (2018)).
- Material stocks in Germany's non-domestic buildings: a new quantification method (R. Ortlepp, K. Gruhler and G. Schiller (2015)).
- Spatiotemporal characteristics of residential material stocks and flows in urban, commuter and rural settlements (P. Gontia, L. Thuvander and H. Wallbaum (2019)).
- GIS-based analysis of Vienna’s material stock in buildings: GIS-based analysis of material stock in buildings (F. Kleeman, J. Lederer, H. Rechberger and J. Fellner (2017)).

This series of methods are based on a material intensity calculation approach which has been chosen due to the availability of data on volume and available living floor space provided by official statistics for the city of Hamburg.

Additionally, in order to determine and predict the amount of future waste material flows resulting from construction, renovation and demolition activities, the following method has been applied:

- Projection of construction and demolition waste in Norway (H. Bergsdal, R. A. Bohne, H. Rechberger and H. Brattebø (2017)).

Relative modifications in factors and other measures have been made in order to build a representative methodology for the particular case of the city of Hamburg

3.3.1 Material intensity calculation approach

To improve the knowledge of materials stocks and flows, a material flow analysis (MFA) is needed using material composition indicators (MCIs). There are various methodologies available for calculating or estimating current area-level (e.g. district, city) material stock. Although several studies have been focused on this topic over recent years, they remain not applicable and transferable due to lack of documentation or validation regarding uncertainties or they use overly generalized coefficients, without counting the diversity of materials in the building stock (Ortlepp et al., 2016, p. 4; 2018, p. 166). Some approaches consider one single coefficient to calculate the material composition of the entire building stock; other studies consider different coefficients based on the material or building size, but without considering the type of use (Blengini, 2009; Müller, 2006; Bergsdal et al., 2008), or have separated coefficients according to the type of use without considering other building measures. Considering that the material composition varies depending on type of use and age-group of the different buildings, specific material intensities per cubage or available floor size can be obtained for different building categories (Kleemann, Lederer, et al., 2017, p. 370).

Bottom up approach for residential buildings based on the age

Considering common approaches related to Material Flow Analysis (MFA) (Müller et al., 2014), this study can be presented as a static bottom up approach (Ortlepp et al., 2018, p. 166). In contrast with dynamic MFA, it looks at stocks for a single time frame (Ortlepp et al., 2018, p. 166). Top-down approaches provide almost no classification by type of materials and are unable to distinguish between different forms of building stock such as domestic and non-domestic. To determine the material stocks and flows in the building stocks, considerable emphasis has been paid to coefficient-based bottom up approaches, which involve use of building-specific material indicators. The basic method of bottom-up approaches is to multiply some practical measures of the stock or flow of interest by coefficients for characteristic material compositions (MCIs). These coefficients describe the relative content of different material groups depending on the characteristics of the observed building (Ortlepp et al., 2018, p. 166). Commonly, the MCIs are classified in terms of specific use, construction type and age of the buildings (Kleemann, Lehner, et al., 2017). By multiplying the MCI factors (see APPENDIX D) with either the floor space or volume of the building, the total material stock was calculated depending on the age-group of the buildings, the building type by function, etc.. The material composition indicators are expressed in tonnes per square meter and tonnes per cubic meter, respectively. For each material group and building type (equation 1) the mass M of a building material group i of a building type j is determined by multiplying the total floor space $FS(j)$ of the building type j with the respective specific material coefficient $MCI(i,j)$ (Ortlepp et al., 2018, p. 168):

$$M_i, j(MFH) = FS\left(MFH_{synth,j}\right) \cdot MCI_i\left(MFH_{synth,j}\right) \tag{1}$$

Equation 1. Material quantification (MFH) in building-up approach based on age

In this case, the mass flows for each material have been calculated by considering the MCIs provided in the method and the data for the net accumulative living space per year (net addition of floor space, resulting from construction and demolition activities). From the year 1918 to 1979, the data used are those presented on construction activities in residential buildings extracted from Hamburg's annual report 2005/2006, whereas from 1979 more accurate and disaggregated data were found until 2018 (*Statistisches Jahrbuch Hamburg 2005/2006*, n. d.).

Bottom up approach for residential buildings based on the age and their size divided in single and multi-family houses

In this method, the stocks and flows are modeled with a bottom-up approach in order to determine the in-use material stock for residential buildings separately for multi-family houses (MFH) and single-family houses (SFH). The MCIs used present little differences than those used before and are relevant of mass per floor space (Gontia et al., 2020, p. 2). This is normal considering that the first approach involves MCIs as determined in Germany, whereas the second approach is about MCIs considered in Sweden. However, both are North countries, therefore it can be assumed that MCIs are representative (see APPENDIX E). Another limitation is that the age classes are not fitting in great accuracy. In this case, the author proposes MCIs differentiated according to age group for both MFH and SFH. Equation 2 illustrates a simplified mathematical representation of the modelling (Gontia et al., 2020, p. 3).

$$MS_{i,n,m,p}^{t} = \sum X_{i,n,m} \cdot B_{n,m,p}^{t} \tag{2}$$

Equation 2. Material quantification (MFH/SFH) in building-up apprach basedbased on age and size

Being $MS_{i,n,m,p}^{t}$ the in-use material stock estimated for the year *t*, material category *i,* for residential building type *n,* age-class *m*; $B_{i,n,m,p}^{t}$ is the inventory of residential stock, building type *n*, age-class *m* and municipality *p* (Gontia et al., 2020, p. 3). The in-use material stock was determined by applying equation 2. Equation 3 indicates, according to the author, a representation of the retrospective material stock.

$$MS_{i,p}^{t-t_0} = MS_{i,p}^{t} - MS_{i,p}^{t_0} \tag{3}$$

Equation 3. Retrospective material stock quantification in residential buildings

By applying equation 2, it is possible to calculate the overall material stock added per year to the existing in the city of Hamburg. In addition, it is possible to calculate the total existing in the city in the year 2002, the year for which the last records of housing classified by age group are obtained (*Statistisches Jahrbuch Hamburg 2005/2006*, s. f.).

In addition, it is to be evaluated whether the MCIs proposed by the author are comparable with the rest examined methods based on material intensity calculation approach, especially those based on the available floor space.

The error of the indicated MCIs as provided by Gontia et l., 2020 is the result of a sensitivity analysis. From the deviation of the total average coefficient for each age group, a maximum error of 22% was determined (Gontia et al., 2020). The standard deviation for each material-group and age-group is shown with the corresponding MCIs (see ANNEX E). The results indicated a deviation of 30%, from which it follows that there is a greater error due to variations in MCIs per material group than due to variations in total stock MCIs (Ortlepp et al., 2018, p. 10).

Bottom up approach for apartments in residential and non-residential buildings based on the age and volume

In this thesis, a different approach was also applied regarding MCIs that represent material mass per volume, as suggested by Kleemann et al., 2017. The different types of buildings proposed by the author in order to obtain MCIs are residential buildings, commercial buildings and industrial buildings in Vienna, whereas regarding residential buildings there is no differentiation between multi-family houses and single-family houses. Based on the above remarks, in Hamburg “Agricultural and Farm Buildings” and “Non-agricultural Industrial buildings” have been considered as industrial category, whereas “Institutional buildings” and “Office and administration buildings” have been considered as commercial category. In DESTATIS database for these categories there is volume data on building permits between 2000 and 2018.

The particular case of Vienna might prove to be applicable to Hamburg city, taking into account that the prevailing building style in the city for construction before 1960 (Wilhelminian style) are commonly built with brick (Kleemann, Lederer, et al., 2017, p. 370).

Table 3. Specific material intensities for the city of Vienna (construction after 1997) (t/m^3)

Period of construction	Utilization	Mineral materials	Organic materials	Metals	TOTAL
After 1997	Residential	0,380	0,010	0,015	0,410

Period of construction	Utilization	Mineral materials	Organic materials	Metals	TOTAL
After 1997	Commercial	0,430	0,004	0,004	0,440

Period of construction	Utilization	Mineral materials	Organic materials	Metals	TOTAL
After 1997	Institutional	0,430	0,004	0,004	0,440

Note. Reprinted from Kleemann, Lederer, et al., 2017, p. 374.

By combining both the specific material intensities per age class shown in Table 3 and the total material composition of the city by the year 2013 shown in APPENDIX F, the net accumulative stock of material for each group from 2000 and 2018 is calculated.

Since the MCIs were expressed per capita, population record in Vienna updated to 2013 was considered and combined with the material composition provided in that study (SEE APENDIX F). In this way, MCIs per material and per age class were converted into tonnes/m3 that is applicable to Hamburg. According to Eurostat population in Vienna for the year 2013 reached up to 1.741.000.

Bottom up approach for apartments in non-residential buildings based on the function and age

The methodology is same with the previous reported for residential buildings but related to different types of non-residential buildings analogous MCIs. The total material stock of apartments in non-residential buildings is obtained by multiplying data of the annual added floor space indicated in building permits 2008-2018 (as shown in Table 4) by the MCIs shown respectively in Table 5. In addition, the aggregated data of non-residential floor built per age class will also be used to estimate the amount of materials in the existing non-residential buildings (see APPENDIX A). The amount of existing non-residential buildings was obtained by deducting the aggregated data for the residential buildings from overall building stock (*Statistisches Jahrbuch Hamburg 2005/2006*, n.d., p. 93)

Table 4. Material intensities depending on the type of non-residential building

Type of building	MCI (t/m2fs)
Institutional Buildings	2,1
Office and Administrative Buildings	2,6
Agricultural Commercial Buildings	1,1
Factory and Workshop Buildings	2,5
Trade and Storage Buildings	2,4
Hotels and Restaurants	2,0
Other non-domestic buildings	3,2

Table 5. Percentage of each type of material group for non-residential buildings

Product groups	Percentage
Plaster, scree, mortar	13,40
Concrete	36,70
Masonry	19,50
Building boards	0,30
Wood, engineered timber	2,20
Insulation materials	0,90
Roof covering	0,30
Floorings, damp-proofing	2,70
Other materials, fills	16,00
Metals	7,80
TOTAL	100,00

3.4 Methods intended for the prediction of waste derived from the construction sector

This method proposes a procedure for estimation of future waste amounts produced from construction, renovation, and demolition, determining specific waste generation factors related to each activity. Especially, the material flows converted into waste is estimated (Bergsdal et al., 2008). The procedure applied for the projections consists of the steps listed below:

1. Estimate the level of construction, renovation and demolition activities in the city of Hamburg. New constructions and completed buildings are presented in the updated annual reports from the city (*Statistisches Jahrbuch Hamburg*, n. d.). Demolition and renovation activities present in the database DESTATIS, provided by the Federal Statistical Office.

2. Apply the specific waste generation factors proposed by the method (kg/m^2) for different material groups. For construction and demolition activities the factors used are those implemented in the previous section – MCIs. For renovations the waste generation factor was determined analogously to the one used by Bergsdal et al. (2008) considering relative conditions in Hamburg.

3. Calculate the overall waste generation projections (tonnes/year) on the basis of growth scenarios.

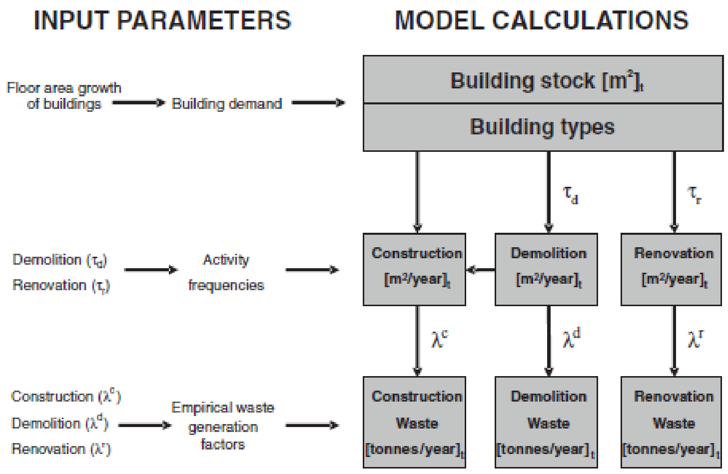


Illustration 13. Outline of stocks and flows model for projecting future waste generation from the construction.

Note. Reprinted from Bergsdal et al., 2008*,* p. 29

In this case, the specific waste generation factors (see APPENDIX F(a)) are framed in ten corresponding material groups, considering: asbestos, hazardous, concrete/bricks, gypsum, glass, insulation/eps, metals, paper/plastics, wood and other unknown materials. The factors are also differentiated according to the type of activity carried out (construction, renovation, or demolition), and in turn, differentiate based on the size of the building, i.e. small (single-family house), large (multi-family house) and other type of residential buildings. All the factors are presented in kilograms per square meter.

It should be mentioned that a series of assumptions have been made to describe the behavior of the housing stock in Hamburg in the future. First, the future construction activity is assumed to increase at a rate of 0,55 % corresponding to the medium population growth predicted for the city of Hamburg according to DESTATIS “*Projected population figures: Länder, reference date, variants of the population projection*”. The annual growth rate has been calculated considering the projected population for each year, which differs according to three different starting assumptions:

- Average migration balance of 147000.
- Average migration balance of 221000.
- Average migration balance of 311000.

For these three scenarios, it is considered that the average birth rate in the city of Hamburg is expected to be 1,55 children per woman. The life expectancy at birth for the year 2060 is expected to be 84,4 years for boys and 88,1 years for girls. DESTATIS provides a prediction beholding all the years from 2020 until 2060. In this study, in order to obtain a feasible growth rate for the city, the average growth for the five-year period between 2019-2025 is to be considered. Furthermore, the three scenarios described above have been also considered to obtain a realistic average.

The basis for determining the waste for each of the three activities lies in the determination of fixed time horizons regarding the average building lifespan. These temporal horizons are shown in Table 6. They differentiate between first renovation, second renovation and demolition, both for large buildings and small buildings (single-family buildings).

Table 6. Expected average time (in years) until renovation and demolition

Activity	**Large buildings**	**Small buildings**
Renovation	40	40
Demolition	80	80

Combining the average life time of buildings with the waste generation factors in Hamburg (see APPENDIX D), waste generation, *W(t)*, is projected according to the following equation developed by Bergsdal et al., 2008:

$$\mathrm{W(t)}_{\mathrm{act,bt,j,t}} = \mathrm{A(t)}_{\mathrm{bt}} \cdot \lambda^{\mathrm{c}}_{\mathrm{bt,j}} + \mathrm{A(t\text{-}40)}_{\mathrm{bt}} \cdot \lambda^{\mathrm{r}}_{\mathrm{bt,j}} + \mathrm{A(t\text{-}80)}_{\mathrm{bt}} \cdot \lambda^{\mathrm{d}}_{\mathrm{bt,j}} \qquad \forall \mathrm{act, bt, j, t} \tag{4}$$

In order to apply equation 4, A(t) is assumed to be equal to:

$$A(t) = A(2016)\left(1 + \frac{0{,}55}{100}\right)^{t} \tag{5}$$

This equation characterizes the growth rate expected due to the considered assumptions. The predictions are made from the year 2016 so that they can be directly compared to existing waste projections published in the “Gemeinsamer Abfallwirtschaftsplan für Bau- und Abbruchabfälle von Hamburg und Schleswig-Holstein”. This comparison will be made in order to validate the obtained results.

It should be noted that in order to obtain the amount of waste materials derived from the demolition activity, it is necessary to define an average demolition period for the residential stock. Since it was not possible to find precise data on this subject for Hamburg, a nationwide search for statistics was carried out on this topic. The average life expectancy for residential buildings in Germany has been determined at a total of 77 years (Ortlepp et al., 2016, p. 38).

In the case of renovation activities, no precise statistics have been determined in Hamburg. For this, statistics provided by companies within the home renovation sector have been used. The average time for renovating homes in Germany is estimated at between 30 and 50 years after construction (*Wie lange hält ein Haus* | *Die Lebensdauer einer Immobilie* | *Baumensch*, n. d.). In order to obtain a fixed period for the application of the subsequent calculations, an average renovation period of 40 years has been considered for the total of the city’s buildings. These considerations only arise so that fair values of waste material can be determined in future years. It should be noted that these values do not constitute precise statistics and are established as an average value, since they vary according to the construction techniques used (Ortlepp et al., 2016, p. 38).

In order to obtain predictions on the city's waste material flows for a future period of 20 years, with a perspective to 2040, values of MCIs for buildings built in the time frame from 1949 until 1978 will be used for calculation of in-net material stock in residential buildings (multi- and single- family houses) (see APPENDIX D and E). The use of the factors proposed for the calculation of material added to the total stock of the city is based on the premise that the total of materials present in a given building will become, in its entirety, waste material after the average life period.

For the prediction of waste generated during the construction and renovation activities of individual buildings, a comparison has been made based on the waste ratios of these activities with the demolition activity for multi- and single- family houses (total stock of the building in use). This will make it possible to determine what proportion of the total building will come waste during each life phase and obtain subsequent coefficients (SEE APPENDIX F(b) and F(c)). Specifically, in order to determine these proportions, the relations between the different waste coefficients proposed by Bergsdal, Bohne and Brattebø (2008) have been used (see APPENDIX F(d)),by dividing the coefficients for construction and renovation activities, respectively, by those for demolition activity.

In the case of renovation activity, the coefficients proposed for the time frames between 1979 to 1990 and 1991 to 2000 have been used to calculate the waste flows generated by this activity 40 years after its construction. The proportionality indicated in the previous case shall be applied to these coefficients. Analogously, for the waste generated in the construction activity, the coefficients proposed for buildings constructed from 1991 onwards have been applied.

Since there is no available disaggregated data regarding available living floor space for the period between 1949 and 1978, an estimate of construction activity will be made on the basis of economic indicators, specifically GDP. There is evidence that the GDP, especially in a period of significant reconstruction, has a linear relationship to the country's construction activity, whose main indicator is the Construction Value Added (CVA) (Lewis, 2008). Furthermore, Strassmann (1970) pointed out that construction sector had overcome manufacturing and as a vector for economic growth in countries that had initiated the process of economic development (Lewis, 2009).

In the case of West Germany, a comparable case of reconstruction can be observed from 1949, beginning the period known as "The German Economic Miracle", which lasted until the 1960s and represented a growth in the country's GDP of nearly 300% between the 1950s and the 1970s (Eichengreen & Ritschl, 2009). In view of the evidence found, this study will proceed to make a distribution of the total residential housing built in the city of Hamburg between 1949 and 1978, according to the presented growth of GDP for that year. In turn, direct proportionality has been assumed between data on construction activity in residential buildings and GDP growth rates.

4 RESULTS

4.1 Results of material intensity calculation approach

4.1.1 Bottom up approach for residential buildings based on the age

The bottom up methods followed in this study have revealed the amounts of materials for the identified building typologies in Hamburg. The amounts per material are presented in histograms showing amount in tones and are classified by the building construction year.

This method, as highlighted in the subsection "Material intensity calculation approach", the final material stock is determined from the net growth of the available floor space and the MCIs shown (SEE APPENDIX C).

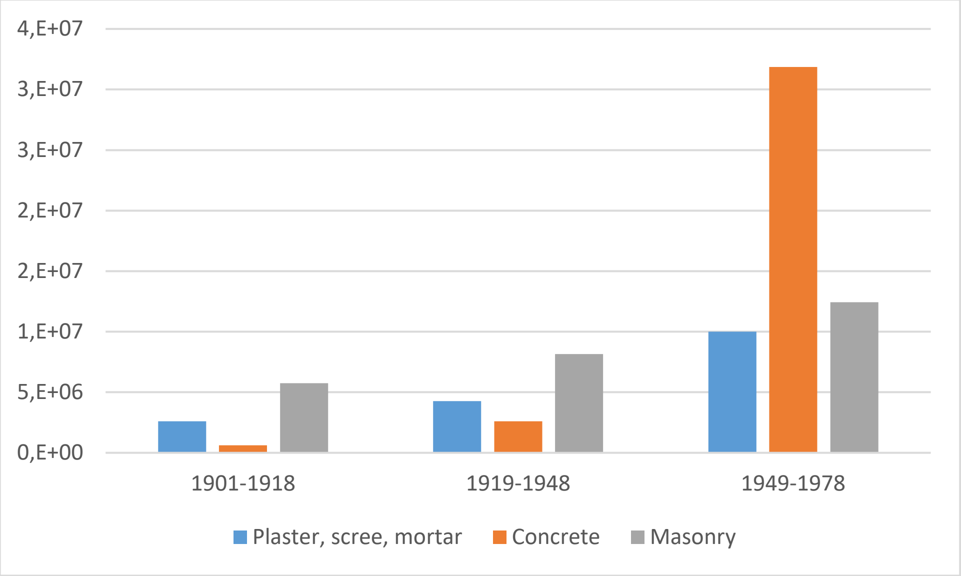


Illustration 14 . Material stock (plaster, concrete and masonry) in tones added per year during the period 1901-1978 for apartments in residential buildings

Illustration 14 demonstrates the amount of paster, concrete and masonry added to the total stock of the city's residential building stock in three different periods. It can be seen that the construction activity is higher between 1949-1978 and specially the use of concrete presents a sharp increase, from less than 5 million tons of concrete added to the city's total material stock for the period between 1919 and 1948, to a quantity of more than 30 million between 1949 and 1978.

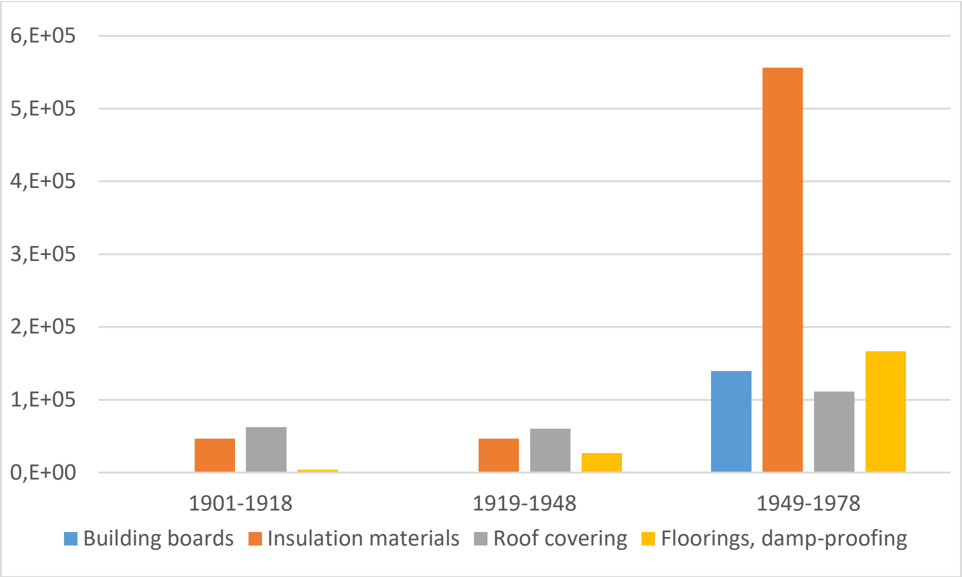


Illustration 15. Material stock (building boards, insulation materials, roof covering and floorings) in tones added per year during the period 1901-1978 for apartments in residential buildings

Illustration 15 shows the material added to the total stock of the city for the different age groups of the buildings present in the city of Hamburg, presenting especially building boards, insulation materials, roof covering and floorings. It is worth noting the enormous increase in the use of insulation materials for buildings constructed between 1949 and 1978. This fact arises from the widespread information campaigns carried out by European governments in order to make households aware of their energy use (*Towards a more sustainable future*, n.d., p. 13). The awareness of the energy problem and the continuous increase of energy price have high investment in measures to reduce and change the use of energy sources (*Towards a more sustainable future*, n. d., p. 13). In Illustration 16 it is possible to identify an increase of about 200.000 tonnes of concrete added to the total stock of the city of Hamburg in 2013, with respect to the amount added in the year 2012. In turn, as can be seen in Illustrations 10 and 11, a high quantitative leap occurs in the input of various materials for the year 2013 with respect to 2012. The leap in the input of materials that occurs in 2013 with respect to 2012 is determined by an increase of nearly 50% in construction activities. On the contrary, the trend prior to

2012 is steady due to the fact that construction activity levels remain practically constant between 2000 and 2013. At the same time, there are two notable increases in the amount of land built on annually for the years 2005 and 2018, which will result in an increase in the input of material.

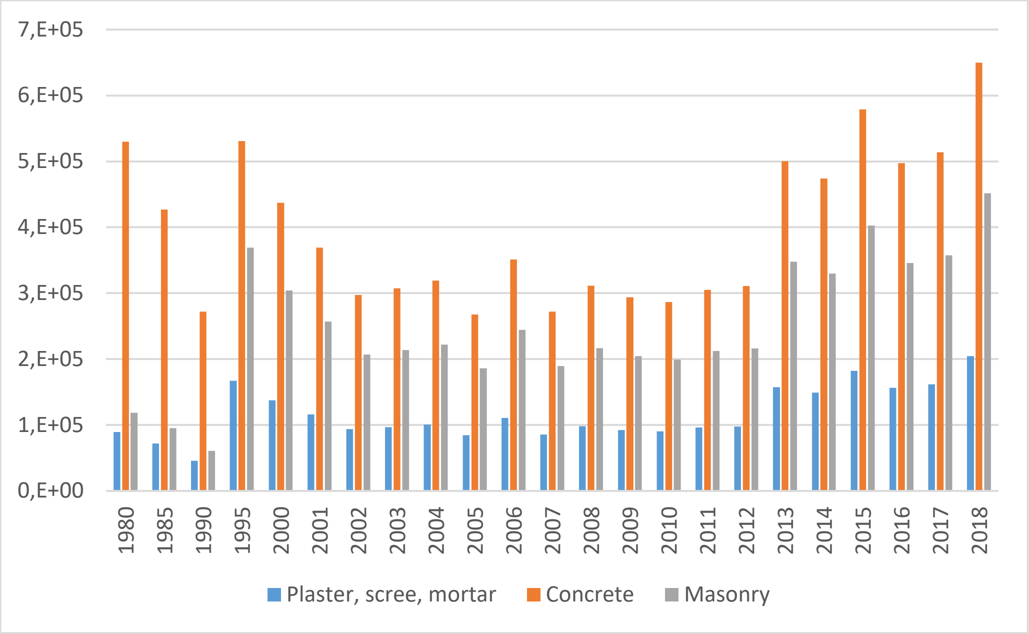


Illustration 16. Material stock (plaster, concrete, and masonry) in tones added per year during the period 1980-2018

As shown in Illustration 16, in 1995, it can be observed a notable increase in the proportion of masonry used with respect to the proportion of concrete and plaster. Afterwards, the proportions between the different materials have been remained constant depending though on the new added living floor space. It should also be noted that in the case of the time frame between 1980 and 2000, only data provided by the city of Hamburg is available in aggregated form.

According to the calculations made, as indicated in the Illustration 16, the material that has been added in greater quantity to the city's stock between 1901 and 2018 is, as expected, concrete, which represents 40% of the added material stock. Next would be the masonry and plaster, representing proportions of 29% and 18% respectively. In a smaller proportion, metallic materials will be found, representing 5% of the total stock added to the city between 1901 and 2018.

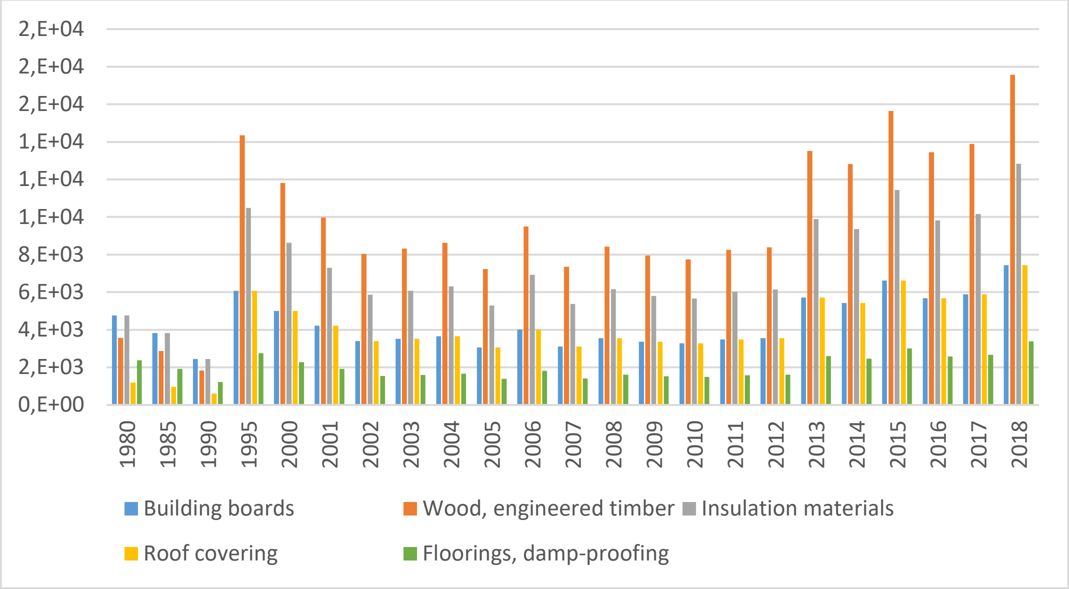


Illustration 17. Material stock (building boards, wood, engineered timber, insulation materials, roof covering and floorings) in tones added per year during the period 1980-2018 for apartments in residential buildings

Table 7. Total material stock added to the city of Hamburg from 1901 to 2018 for apartments in residential buildings

	Total
Product groups	t
Plaster, screed, mortar	19560280
Concrete	44193762
Masonry	32067841
Building boards	240095
Wood, engineered timber	1138099
Insulation materials	816285
Roof covering	326667
Floorings, damp-proofing	243899
Other materials, fills	6914061
Metals	4851830
TOTAL	110340938

Table 7 details the total amount of each material (in tonnes) added to the city's total stock in the period between 1901 and 2018. In turn, Illustration18 shows the composition of the stock of added material in this period. As can be seen, concrete represents 40% of the total added stock, followed by masonry, which represents 29%. Furthermore, wood accounts for 18%, while metals account for 5%.

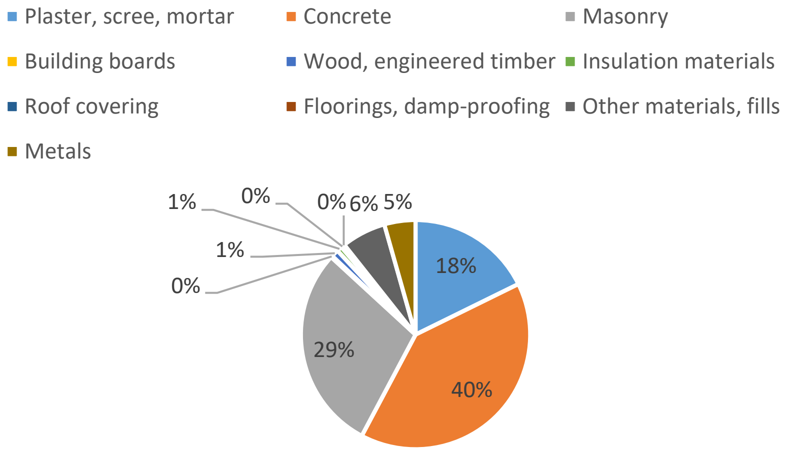
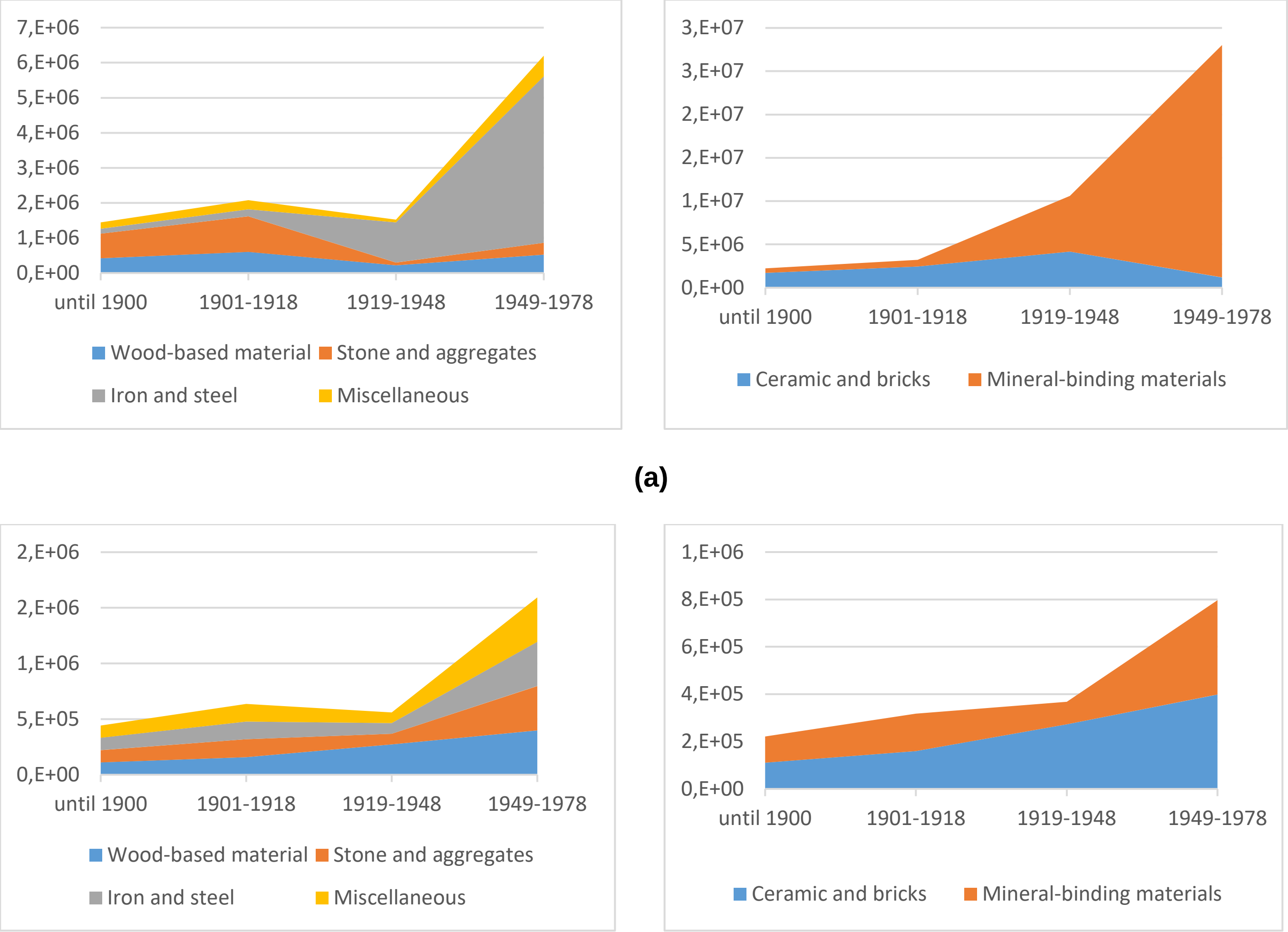


Illustration 18. Total in-use material stock from 1901-2018

4.1.2 Bottom up approach for residential buildings based on the age and their size divided in single and multi-family houses

More detailed results involving separately amount in single- and multi-family houses were used and the amount of materials per age class is shown in the following figures.

In Illustration 19 (a), which shows material input variations for MFH between 1900 and 1978, it is possible to observe an almost steady trend in the input of wood-based materials. In the case of stone and aggregates, the amount fluctuates since it is the predominant fraction in the period between 1901 and 1918 (nearly 50 % of the total), turning to a negligible fraction in the following period. On the contrary, in the case of metals, there is a high increase between the period between 1901 and 1918. Specifically, the metal fraction represents a small proportion of the total composition of buildings until 1948, but after metallic materials represent a majority share of the total. Furthermore, there is a notable increase in the input of material per period, from a total of 2.000.000 tones between 1901 and 1918, to 6 million tons between 1949 and 1978. Illustration 19 (b) shows the trend in material inputs for SFH stock during the same time periods presented for MFH. In this case there is also a notable increase in the period between 1949 and 1978 going from 600.000 tons to 2.000.000.



(a)

(b)

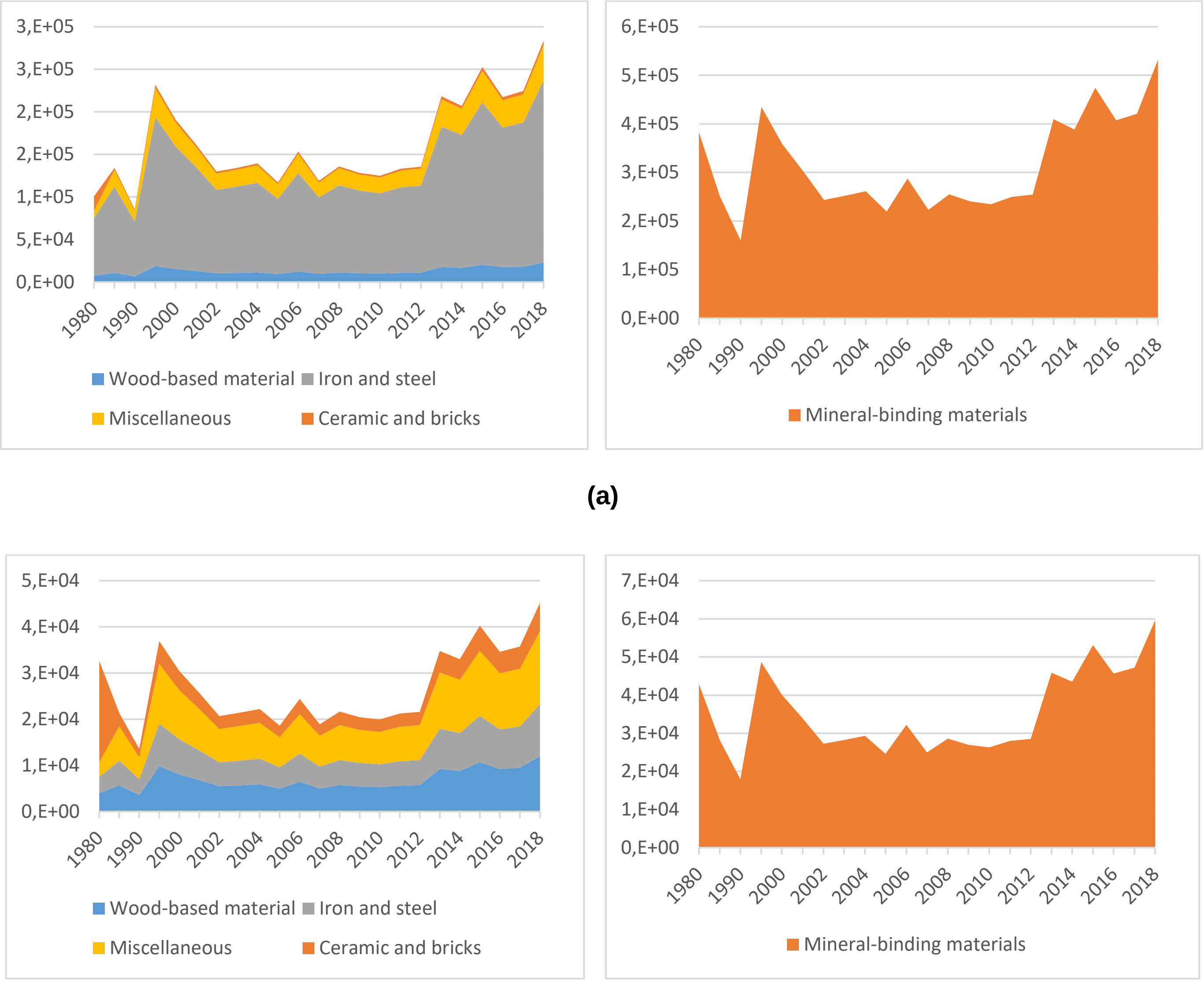
Illustration 19. Material stock in tones added per period between 1900 and 1978 to the (a) MFH stock and (b) SFH stock

At the same time, as it is shown in Illustration 19 (a) for MFH, in the case of ceramic materials and bricks, there is a constant evolution in the input trend. In the period between 1901 and 1918 these materials have been used in a much higher proportion than the mineral-binding materials.

The use of mineral-binding materials has been increased from representing a small proportion of the input between 1900 and 1918 to 500.000 tons between 1919 and 1948. In the period between 1949 and 1978, the mineral binding-materials represent and input of nearly 35 million tons, while the ceramic materials input represent 2,5 million.

In the case of Illustration 19 (b), it is possible to highlight a practically constant proportion between the input of ceramic materials and bricks, and the input of mineral binding-materials in SFH housing stock. For both groups of materials, this input will go from 100.00 tonnes before 1900, to an input of 400.000 tonnes in the period between 1949 and 1978.

When comparing Illustration 19 (a) and (b), it is possible to observe a higher proportion of mineral-binding material use for MFH than for SFH from 1948 onwards, while in SFH these materials and the ceramics are presented in equal proportion. In turn, Illustration 19 (a) shows a significantly higher proportion of metals in MFH than in SFH in relation to the other materials. In view of the results, as expected, it is possible to observe a predominance of metallic materials in MFH, whereas SFH present higher proportion of ceramic/bricks and wood.



(a)

(b)

Illustration 20. Material stock in tones added per period between 1980 and 2018 to the (a) MFH stock and (b) SFH stock

As in the previous case, in Illustration 20 (a) and (b) it is possible to observe a practically steady wood input in the period between 1980 and 2018. In the case of metallic materials, a much higher proportion is observed for MFH than for SFH in relation to the other materials. On the contrary, in the case of ceramic materials, the proportion is higher in the case of SFH. For mineral-binding materials the main differences will come from the difference between the number of apartments in MFH and SFH, along with the difference in the MCI used (0,788 t/m^3 in MFH and 0,204 t/m^3 in SFH).

In this case, the total results are presented both for large residential buildings and single-family houses in order to facilitate further comparisons. The overall results for the overall in-use material stock from the year 1901 until 2018 are presented in Table 8 and respectively Table 9.

Table 8. Total in-use material stock in the city of Hamburg within MFH from 1901 until 2018

	Total
Product groups	t
Wood-based materials	2079296
Ceramic materials	9577091
Mineral-binding materials	41874752
Stone and aggregates	2134496
Iron and steel	9063333
Miscellaneous	1651456
TOTAL	62404100

Table 9. Total in-use material stock in the city of Hamburg within SFH from 1900 until 2018

	Total
Product groups	t
Wood-based materials	1089452
Ceramic materials	1016032
Mineral-binding materials	1504687
Stone and aggregates	764012
Iron and steel	904373
Miscellaneous	960517
TOTAL	2063973

In this case, a comparison with Illustration 18 for "*Bottom up approach for residential buildings based on the age"* shows clear differences between these two approaches. It is worth noting that the first approach focuses primarily on building elements, while the second indicates raw building materials. First, it should be noted that the two approaches are not completely comparable since the first considers all residential stock in a global way, whereas the second discerns between SFH and MFH coefficients. Both cases, as expected, show a higher proportion of mineral-binding materials in relation to other materials. Illustration 21 for MFH shows a proportion of 63% mineral-binding materials, while in Illustration 22 it represents a 24% of the total. In the case of the previous approach, the proportion of concrete is 40%, approximately the average between these two values.

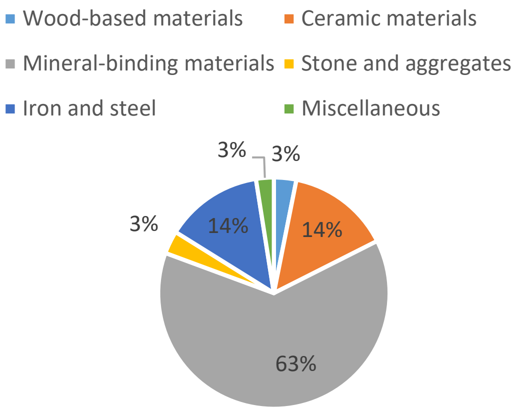


Illustration 21. Total in-use material stock for MFH from 1901-2018

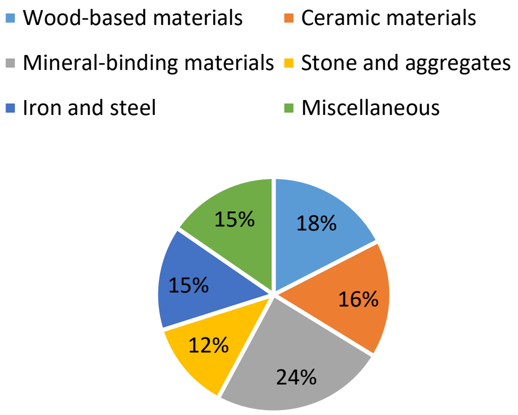


Illustration 22. Total in-use material stock for SFH from 1901-2018

With a critical view, it is possible to propose that in order to evaluate the stock of materials in the city of Hamburg, it is more appropriate to use the coefficients of the second approach by applying a series of considerations particularly for MFH. It is possible to observe that the quantities of wood are practically the same in both cases. In contrast, at the expense of differences in the use of ceramic materials and masonry, the second approach shows a proportion of 14% for MFH, which is significantly lower than the first approach of 28%. This leads to the conclusion that the coefficients lead to an underestimation of the quantities of ceramic materials in the city of Hamburg.

Table 10. Total in-use material stock in the city of Hamburg 1901 until 2018 with a bottom up approach based on age

	Total
Product groups	t
Plaster, screed, mortar	19560280
Concrete	44193762
Masonry	32067841
Building boards	240095
Wood, engineered timber	1138099
Insulation materials	816285
Roof covering	326667
Floorings, damp-proofing	243899
Other materials, fills	6914061
Metals	4851830
TOTAL	110340938

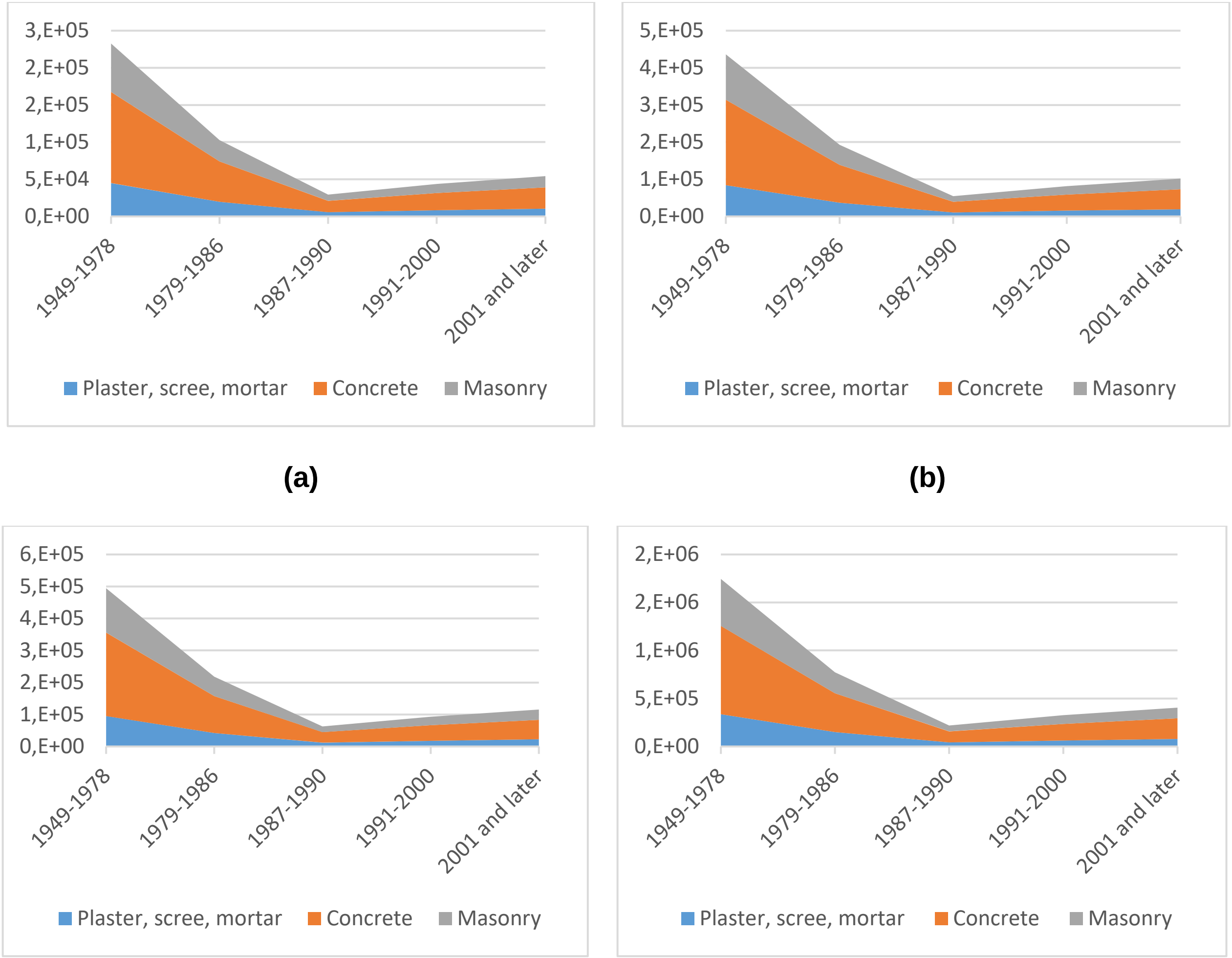
Table 11. Total in-use material stock in the city of Hamburg from 1901 until 2018 with a bottom up approach based on age and building type

	Total
Product groups	t
Wood-based materials	3168748
Ceramic materials	10593123
Mineral-binding materials	43379439
Stone and aggregates	2898508
Iron and steel	9967706
Miscellaneous	2611973
TOTAL	64468073

Tables 10 and 11 respectively show the material input results for the age-based, and age and building size respectively. Regarding the quantities of concrete obtained, it should be noted that both are practically identical, reaching 44.000.000 and 43.000.000 tonnes. In the case of wood, quantities obtained are 200% higher for the second approach. This is due to higher MCIs for all periods and types of buildings. When comparing both approaches, it can be seen that the main differences between the total quantities (110.000.000 and 64.000.000) are due to the significant difference between the inputs of ceramic materials and masonry. In the first case, the input of ceramic materials is 32.000.000 compared to nearly 11.000.000 in the second.

4.1.3 Materials in Germany’s non-domestic building stock: a new quantification method

In this case, the results obtained from the application of the method indicated for non-residential buildings will be analyzed.



(a)

(b)

(c)

(d)

Illustration 23. Material stock in tones added per year during the period 1949-2001 to the (a) institutional (b) office and administration (c) agricultural and farm (d) non-farm industrial building stock

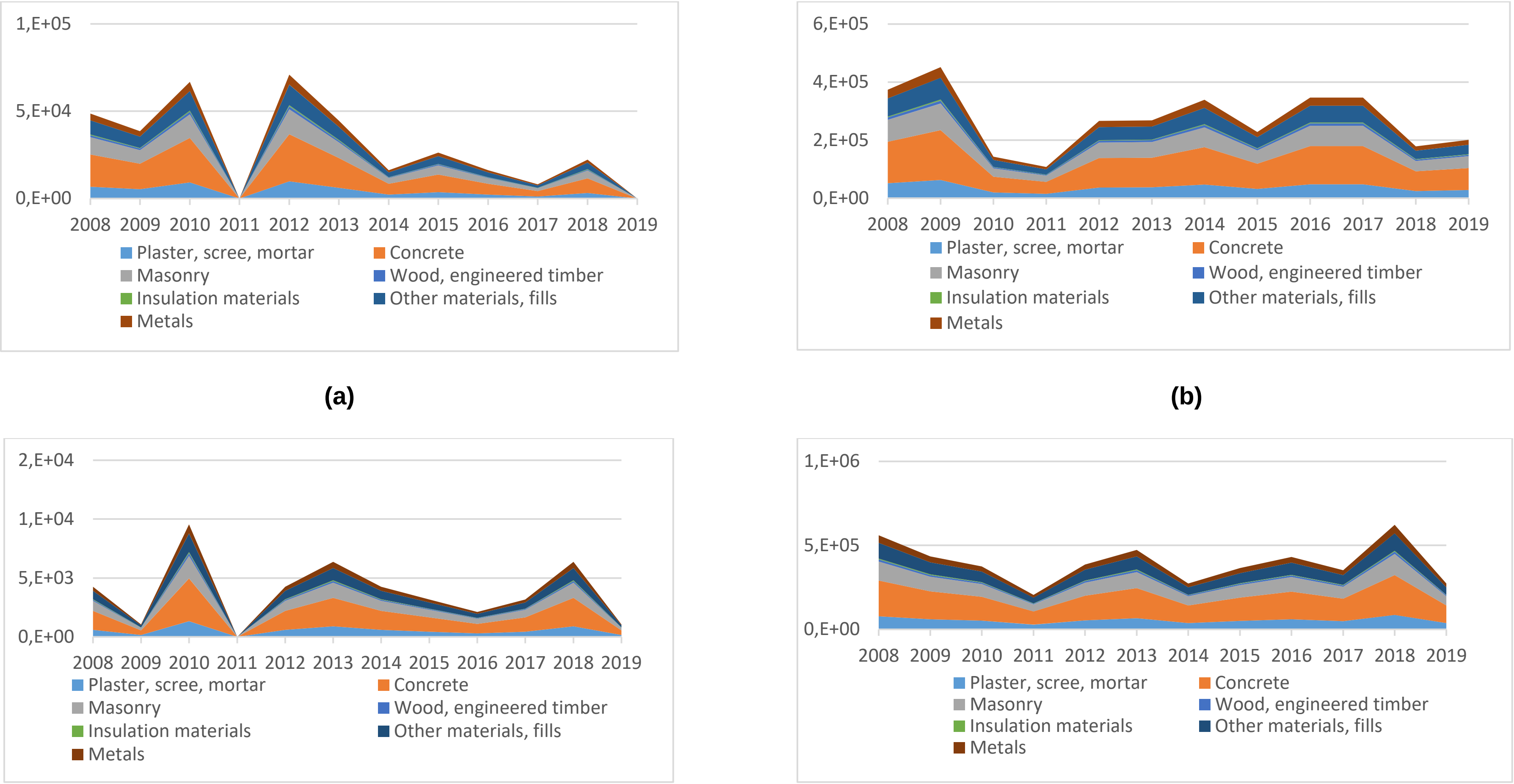
In the case of Illustration 23, a trend can be observed between 1949 and 2001 in which the material input is practically identical for the different types of non-residential buildings (institutional, office and administration, agricultural and farm and non-farm industrial buildings). The differences are given only and exclusively by the different MCIs for each of the building types. In turn, due to the absence of data for annual construction of non-residential buildings up to 2008, the available data have been used and the percentages for each of the uses have been applied according to Ortelpp, et al. (2015). For all four types of buildings it is possible to observe a decrease of approximately 50% between the period 1979-1986 and the period 1991-2000.

Table 12. Floor space in the non-domestic building stock in 2010 according to type of use; estimates based on gross stock of fixed assets and using a distribution corresponding to building activity from 1997 to 2010

	Floor space
Non-domestic building type	**[%]**
Institutional buildings	4
Office and administration buildings	15
Agricultural and farm building	19
Non-farm industrial buildings	62

Note. Reprinted from Ortlepp et al., 2015, p. 41

As expected from the data in Table 12, non-farm industrial buildings represent the largest input of materials, with approximately 2.000.000 tonnes added in the period 1949-1978. Followed by agricultural and farm buildings and office and administration buildings, which represent 25% of the former. Institutional buildings represent the smallest input, approximately 300.000 tonnes in the period 1949-1978.



(a)

(b)

(c)

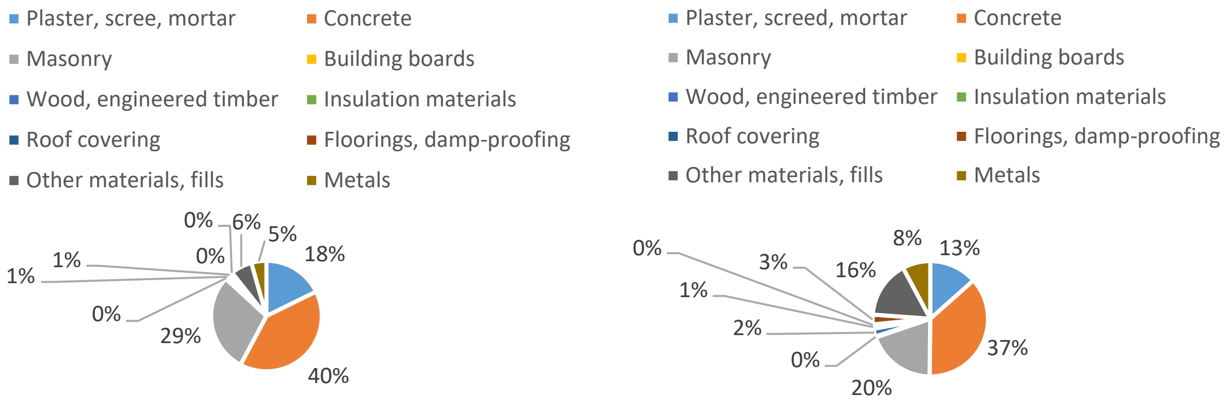
(d)

Illustration 24. Material stock in tones added per year during the period 2008-2019 to the (a) institutional (b) office and administration (c) agricultural and farm (d) non-farm industrial building stock

In Illustration 24, it can be seen that in the period between 2008 and 2019, non-agricultural industrial buildings represent the largest input of material. Illustration 24 (a) and (b) show null activity values in 2011, both preceded and followed by peak values in 2010 and 2012. For both, the input trend will be downwards until 2016, where it started increasing until 2018. In the case of institutional buildings, the maximum value in the graph represents an input of 50.000 tonnes, whereas for agricultural and farm buildings, only 10.000 tonnes. Illustration 24 (b) and (c) show a downward trend between 2009 and 2012, the stabilizing at around 300.000 tonnes for office and administration buildings, and 400.000 tonnes for non-farm industrial buildings. With regard to the trends observed in the previous case, Illustration 23, it can be seen that using real data from the city of Hamburg, the input of materials in agricultural and farm buildings falls while the input in institutional and administrative buildings increases.

4.1.4 Comparison between bottom up approach for residential and non-residential buildings based on the age: available floor space

This section shows the proportions represented by the different materials calculated by means of the “Bottom up approach for residential and non-residential buildings based on the age”.



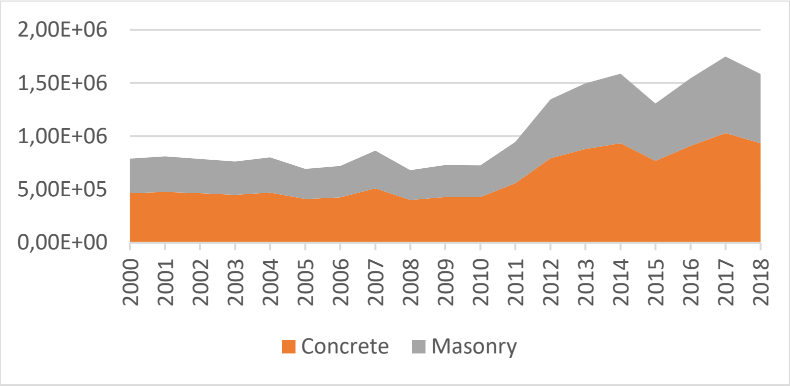
(a) **(b)**

Illustration 25. Materials added to the building stock in (a) residential (b) non-residential buildings permits

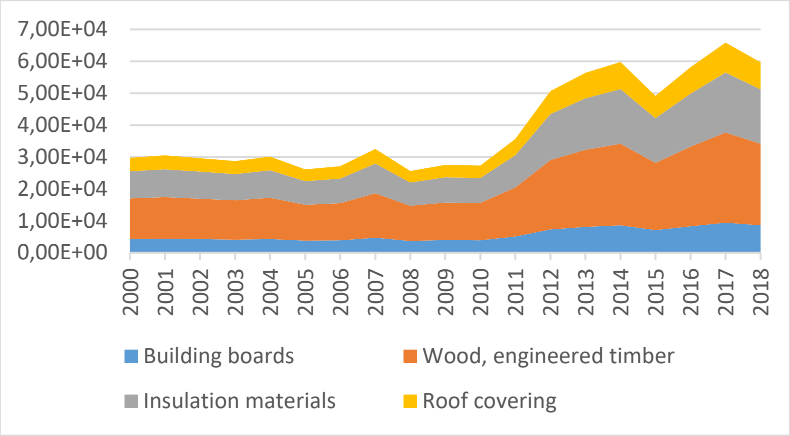
Illustration 25 (a) and (b) show that the proportions of materials for MFH and for non-residential buildings are almost identical. In the case of concrete, the proportion is slightly higher for MFH, 40% of the total. In the case of both wood and masonry, the proportions are 18% and 29% respectively in MFH, compared to 20% and 13% in non-residential buildings. On the other hand, in the case of metallic materials, the proportion is slightly higher in non-residential buildings, 5% in MFH and 8% in non-residential buildings.

4.1.5 Bottom up approach for residential buildings based on the age and use (volume)

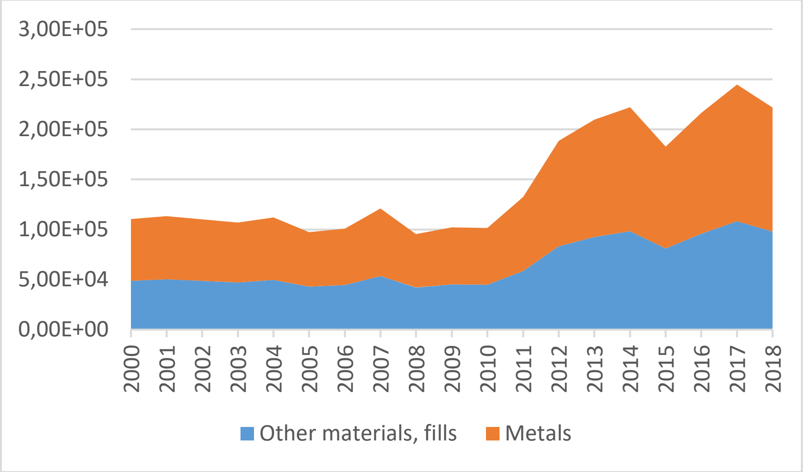
The following will show the results obtained from the MCIs exposed in the method for residential and buildings based on annual building permits. In this case, the balance on the net added material stock per year will only include the years between 2000 and 2018 due to the lack of data on previous years.



(a)



(b)



(c)

Illustration 26. Material stock in tonnes added per year during the period 2000-2018 to the residential building stock

Illustration 26 (a) shows the trend of the value sequences representing the annual input of concrete and masonry. In both cases, there is a notable increase between 2010 and 2014. In agreement with the findings of the bottom up approach that considers the floor space, similar results are shown when volume was considered as measure. Especially, it can be seen that concrete in buildings has been increased after 2010. Furthermore, there is an increase of more than 50% within the whole period of, from an input of 427.000 tons to a value exceeding 930.000 tons in 2014. For the input of masonry Illustration 26 (a) shows an increase of 50% in the same period, going from 325.000 tons in 2000 to 650.000 in 2018.

In Illustration 26 (b), it is possible to identify a similar trend to those described above, with a differentiation in the orders of magnitude between the different groups of materials. The growth in the use of wood-based materials and insulation materials is noteworthy. For the first group, there is an increase close to 50% in the mentioned period, going from 12.700 tons in the year 2000 to 25.600 in the year 2018. In the case of insulation materials, there is also a 50% increase in the initial value, from 8.500 tons in 2000 to 17.000 tons in 2018.

In Illustration 26 (c) it is possible to observe a continuous and stable trend between the years 2000 and 2010. Between 2010 and 2014 there is a notable increase in the input of material for both fills and metallic materials, going in the first case from 57.000 to 124.000 tones, and in the case of metallic materials from 45.000 to 98.000 tones.

Subsequently, both in Illustration 27 and Table 13, it is possible to observe an input proportion of 43% by the concrete. A 30% of the total will be represented by the masonry. Followed by a proportion of 14% of plaster, scree and mortar. In percentages of 6% and 5% are the metallic materials and fills respectively.

Table 13. Estimated material stock based in volume of construction in the city of Hamburg within residential buildings from 2000 to the year 2018.

	Total
Product groups	t
Plaster, scree, mortar	3700125
Concrete	11743875
Masonry	8204625
Building boards	107250
Wood, engineered timber	321750
Insulation materials	214500
Roof covering	107250
Floorings, damp-proofing	53625
Other materials, fills	1233375
Metals	1555125
TOTAL	27295125

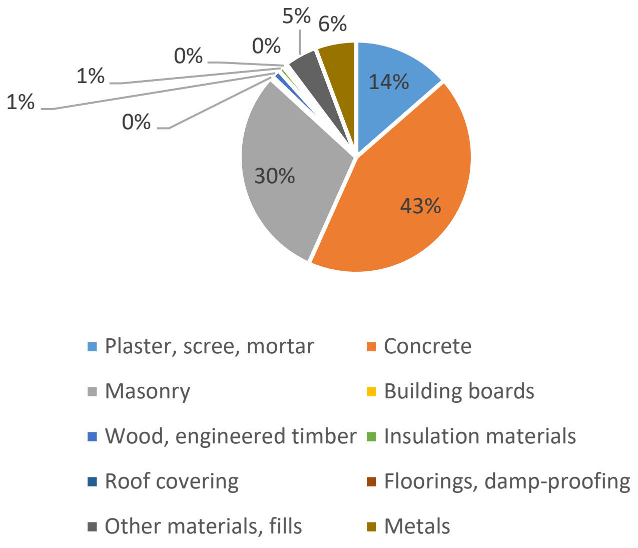
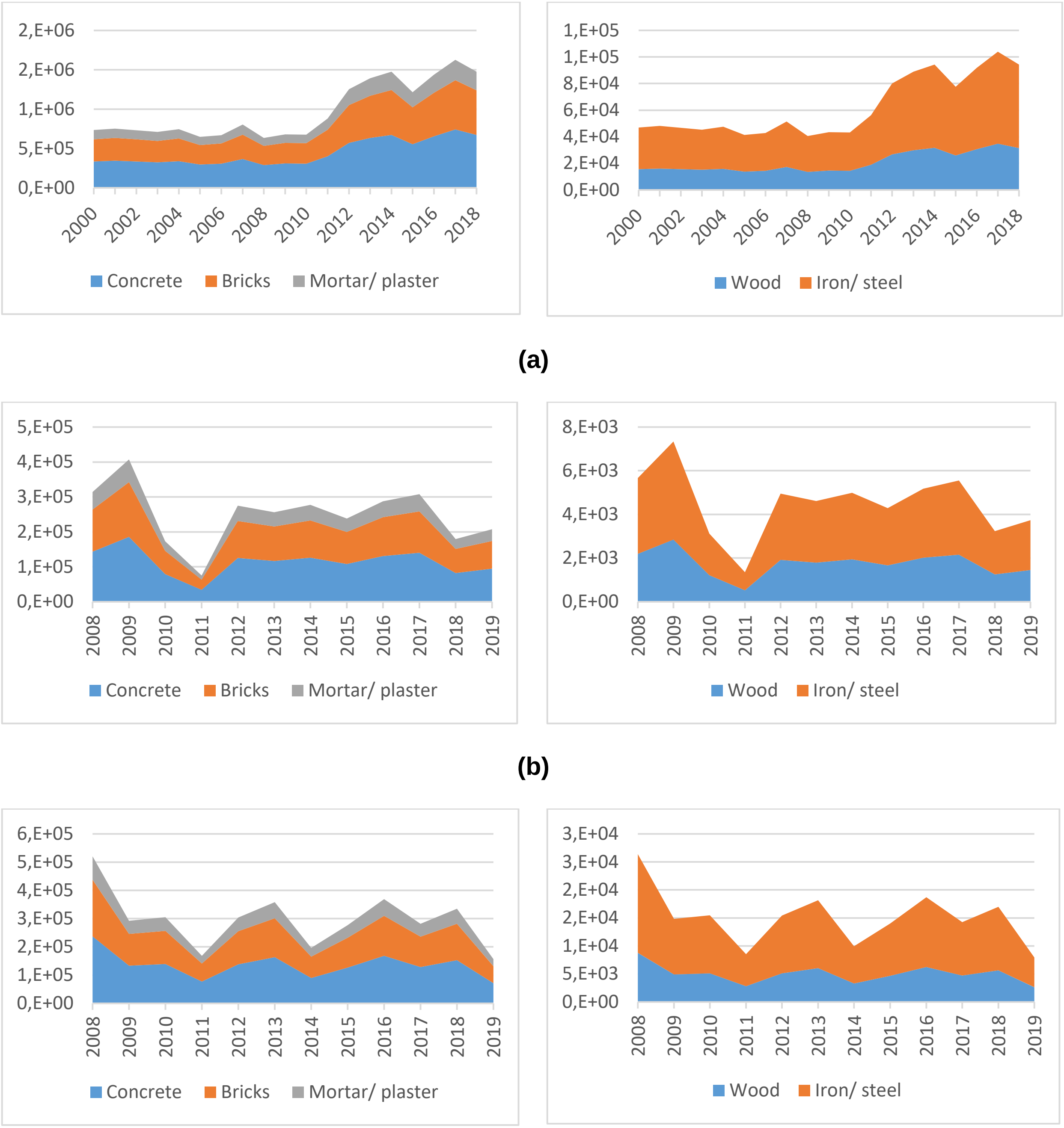


Illustration 27. Total in-use material stock from 2000-2018

4.1.6 Bottom up approach for apartments in residential and non-residential buildings based on the age and use (volume)



(a)

(b)

(c)

Illustration 28. Material stock in tones added per year during the period 2000-2018 (a) in residential buildings, (b) in commercial buildings, (c) in industrial buildings based on building permits

Illustration 28 (a), (b) and (c) shows the input of materials between 2008 and 2019 for residential buildings, commercial buildings and industrial. Illustration 28 (a) shows a steady trend between 2000 and 2012. From 2012 onwards, there is a significant increase in the input. In turn, the quantities of bricks are slightly lower than the quantities of concrete. Going from 500.000 tonnes to 1.000.000 tonnes from 2012 onwards. The amount of metallic materials will also be approximately double that of wood throughout the study period. This will increase from 20,000 tonnes to approximately 40,000 tonnes in 2012 onwards.

Illustration 28 (b) for commercial buildings shows a peak in the input trend for 2009, followed by a decline until 2011. The input will then remain broadly stable over the rest of the period. The amount of concrete, in this case, along with the amount of brick, will be 100.000 tonnes. Approximately 20% of the input in residential buildings. For wood and metals the amounts will be 10% of those for residential buildings.

Illustration 28 (c), for industrial buildings, shows two decreases in input in the years 2011 and 2014. For the rest of the study period, the trend remains almost stable and around 100.000 tonnes per year for concrete and bricks. In these cases, the quantities are comparable to those obtained for commercial buildings. For industrial buildings, the quantities of wood and metals are higher than for commercial buildings, being in the range of 15.000 to 20.000 tonnes per year in the case of metals, and 5.000 in the case of wood.

4.1.7 Comparison between bottom up approach for residential and non-residential buildings based on the age and use: volume

The results obtained from the two volume-based approaches will then be compared, both between residential buildings and between residential and non-residential buildings. The comparison between the results obtained for residential buildings, shown in Tables 14 and 15, will be shown in absolute terms. In the first case, the result for concrete with the "Building up approach based on age" is about 12.000.000 tons, while with the second approach it is 8.500.000. In turn, the amounts of masonry and plaster are also slightly lower in the second approach. There are 3.700.000 and 8.200.000 in the first approach, and 3.000.000 and 7.000.000 in the second approach. In the light of the results obtained for the main categories of material (concrete, masonry, plaster and metals) we can say, with a critical eye, that the coefficients in the “*Building up approach based on age and building type”* are generally lower. This raises fact raises a possible underestimation of the MCIs proposed in the second approach.

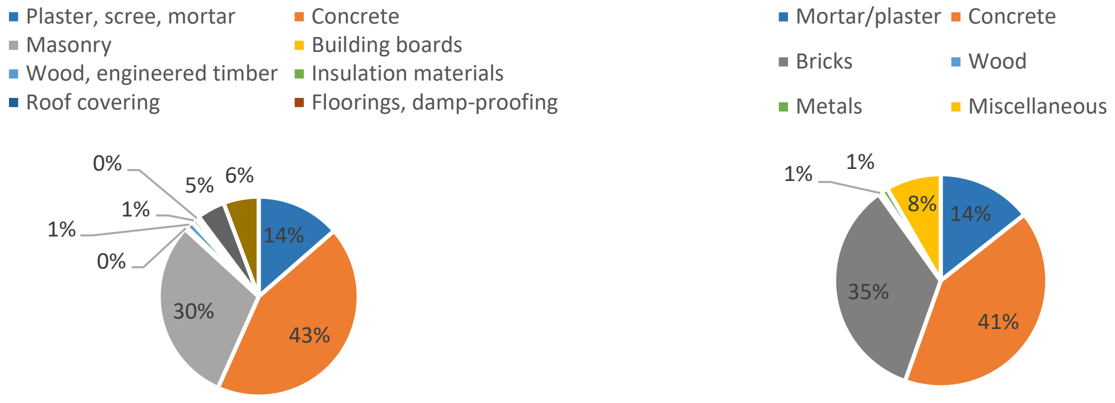
In the case of the comparison for residential and non-residential buildings, shown in Illustration 29, similar results have been obtained in terms of proportions. For concrete, the proportions are 43% and 41% respectively. The proportion of brick is slightly higher in the second approach, being 35% compared to 30% in the first. In the case of plaster and wood, the results are identical, 14% and 1% respectively.

Table 14. Total in-use material stock in the city of Hamburg 2008 until 2018 with a bottom up approach based on age (volume)

	Total
Product groups	t
Plaster, scree, mortar	3700125
Concrete	11743875
Masonry	8204625
Building boards	107250
Wood, engineered timber	321750
Insulation materials	214500
Roof covering	107250
Floorings, damp-proofing	53625
Other materials, fills	1233375
Metals	1555125
TOTAL	27295125

Table 15. Total in-use material stock in the city of Hamburg from 2008 until 2018 with a bottom up approach based on age and building type (volume)

	Total
Product groups	t
Mortar/plaster	2954738
Concrete	8456663
Bricks	7132125
Wood	396825
Metals	804375
Miscellaneous	1771641
TOTAL	21516367



(a) **(b)**

Illustration 29. Material stock added to the stock in (a) residential (b) non-residential buildings (volume)

4.2 Predicting future material stock released

This section will describe the results obtained in terms of quantities of waste material between 2025 and 2040. Illustrations 30 and 31 show these results for the main groups of material in each of the MFH and SFH categories. The amounts of waste from construction, renovation and demolition activities are presented separately. It should be noted that in all cases, the quantities of waste predicted for construction activity are estimated on the basis of predictions of future activity. This model is presented in Illustration 11. The results for this activity show a slight increasing trend in all the cases. Due to this, with a critical view of them, it is possible to state that the waste from the construction activity will remain stable throughout the study horizon. Concrete and brick waste will be relevant in the case of MFH, with 20,000 and 10,000 tonnes of waste respectively every 5 years. In comparison with other materials, the disposal of metallic materials will be relevant in the case of SFH, reaching 500 tonnes every 5 years.

In the case of renovation activity, a significant intensification is expected in the period between 2025 and 2030, which in turn will generate an increase in the amount of waste generated. For MFH, it can be seen that waste derived from renovation activity is more relevant than construction activity in the case of plaster and metals, exceeding the latter by 900%. In SFH, on the other hand, there is a higher proportion of concrete, masonry and wood waste from renovation activity. In turn, the result of the predictions for wood waste in SFH is practically nil for the whole study horizon.

In the case of demolition activity, the results show a downward trend for all materials between 2025 and 2030, followed by a stabilisation for the rest of the period. In Illustrations 30 there is a quantity of demolition waste for concrete and brick of about 1.000.000 and 400.000 tons of waste respectively for periods of 5 years for MFH. For SFH, these quantities will be around 50.000 and 5.000 tonnes. Therefore, for these materials, it is possible to indicate that the quantities of waste in SFH represent approximately 10 to 20% of those in MFH. In the case of metals in SFH, from 2035, an anomalous trend is observed in comparison with other core materials, with this waste increasing by 300% (200 tonnes to 600 tonnes) in 5 years.

It should be noted that, although the calculation was made for the waste materials of all the groups, it was decided to show and discuss only those that presented noteworthy results. In the case of MFH, we have chosen to present plaster waste, while in SFH we have chosen to represent wood waste.

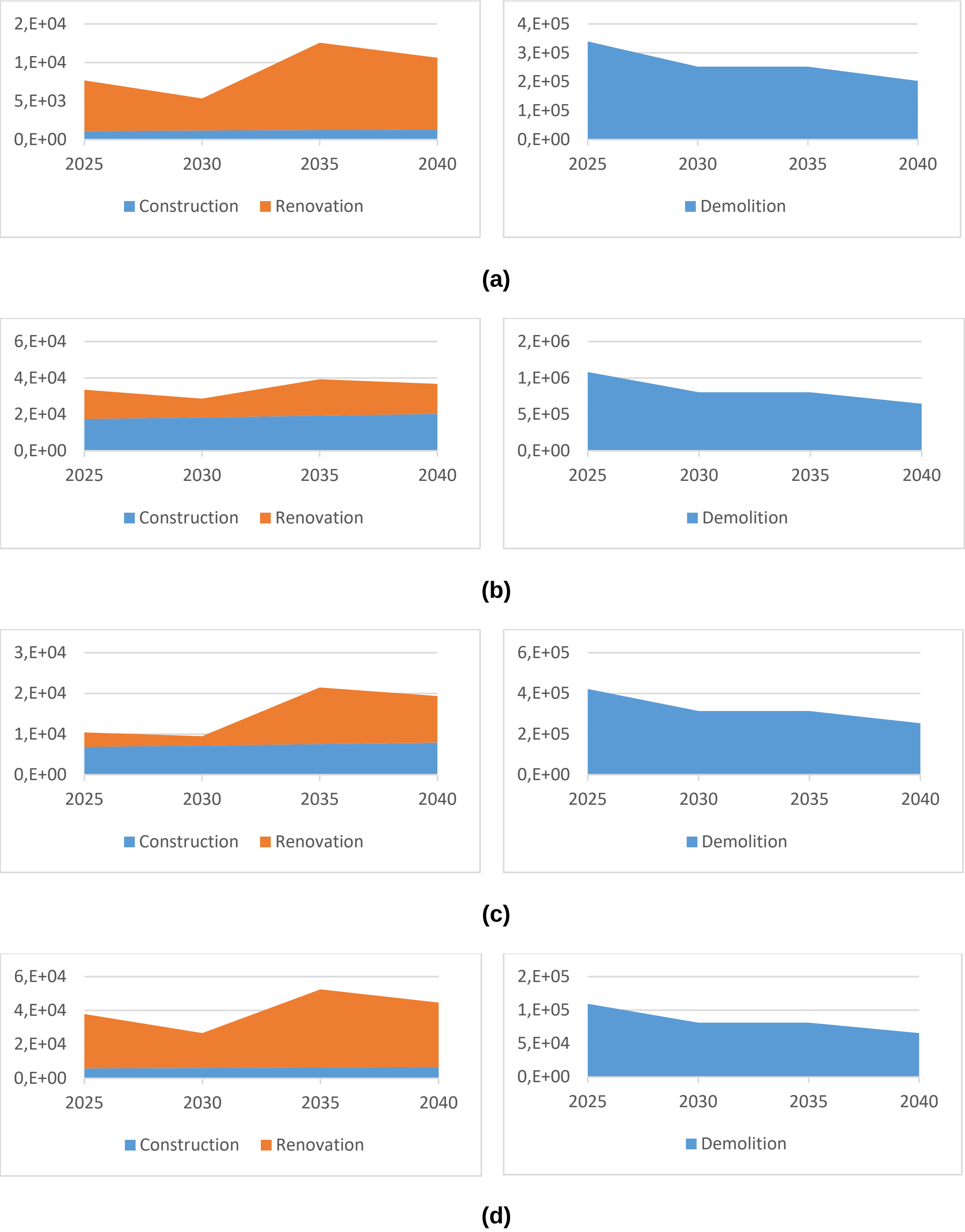


Illustration 30. Waste material predictions in tonnes due to construction, renovation and demolition activities in MFH: (a) plaster (b) concrete (c) masonry (d) metals

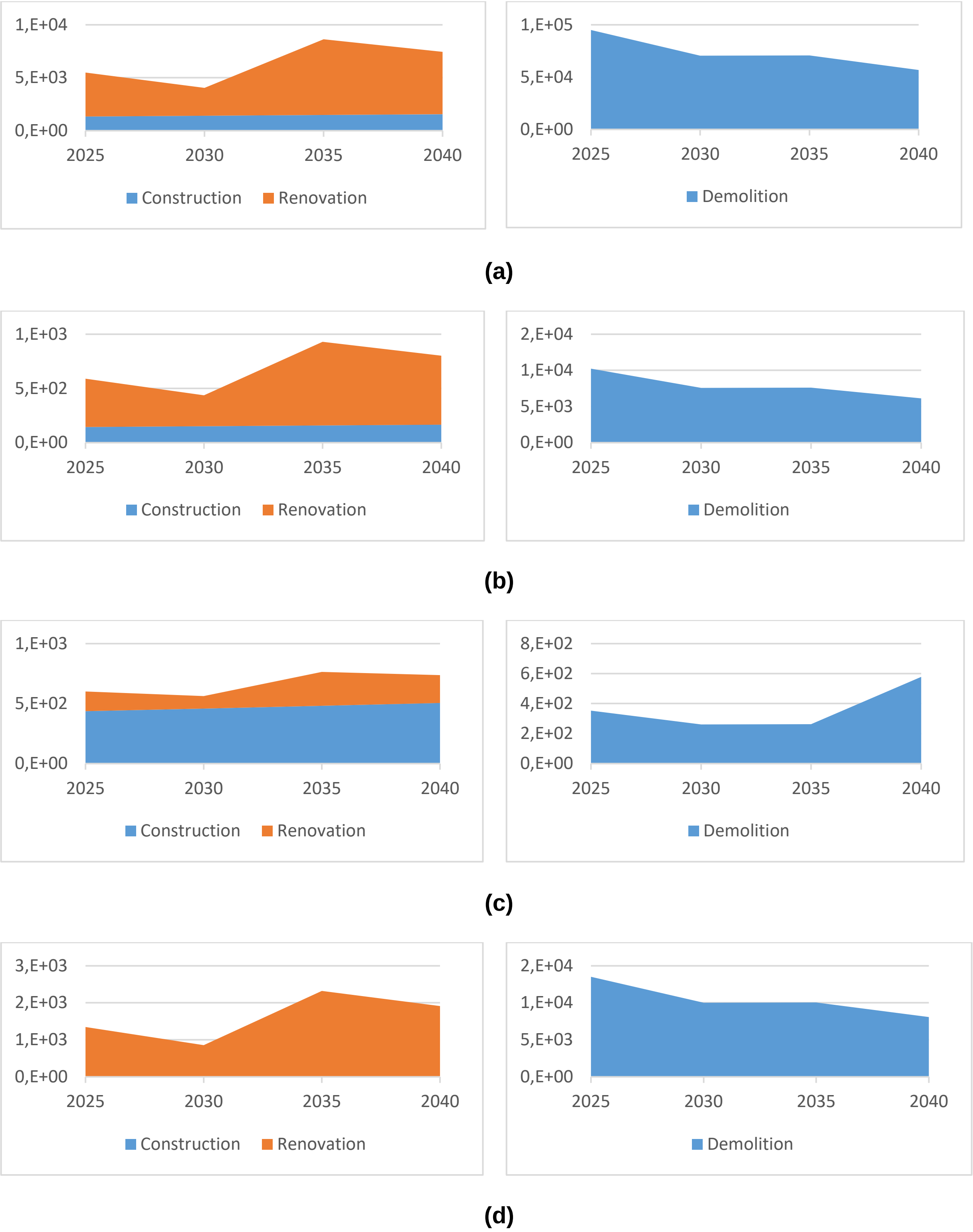


Illustration 31. Waste material predictions in tonnes due to construction, renovation and demolition activities in SFH: (a) concrete (b) masonry (c) iron and steel (d) wood

4.3 Comparison of the different material composition indicators

In this subsection, a comparative analysis has been made between the different MCIs proposed by the different authors considered throughout this study. A comparison of the different factors is shown according to the corresponding input variable, either the added living floor space or the annual volume of construction reflected in the building permits. In turn, a comparison will also be made between the different coefficients proposed in order to calculate the waste derived from construction, renovation and demolition activities, necessary and predict waste flows by 2040. The comparison between the different factors has been made mainly between those corresponding to the core materials (concrete, masonry, wood and metals) used in buildings, since these categories are considered by all researchers and are the most easily extrapolated.

First, a comparison will be made between the most significant aspects of the methods that have the available floor space as an input variable for the calculation of material concentrations. By comparing the MCIs proposed by the "*Building up approach for residential buildings based on age*" (see APPENDIX C), with those proposed by the "*Building up approach for buildings based on age and building type*" (see APPENDIX E), a significantly higher weighting is observed in terms of concrete content. In both cases it is possible to appreciate a notable increase in the weighting of this material from the beginning of the 20th century to the last decades of it. The concentration will increase from 0,161 t/m^2 in the case first case in 1918 to 1,336 t/m^2 in the period between 1979 and 1990, for the second approach within the period between 1930 and 1980, the concentration of the "mineral-binding materials" will increase from 0,204 t/m^2 to 0,965 t/m^2. This increasing trend will be repeated for almost all material concentrations over time. As highlighted in the previous section, the MCIs proposed in the first approach are significantly higher in all cases, particularly in core materials instead of metals.

In the case of wood-based materials, there will be a clear decrease in weighting factors throughout the 20th century. As for bricks and ceramic materials there will be also a significant decrease between the weights of this type of materials for buildings built in 1918, and those more recently built. It is also possible to highlight a higher proportion in the intensities of metallic materials (0,152 t/m^2 and 0,317 t/m^2) in the case of the second approach.

In the following lines, a comparative analysis will be made between the methods that have the construction volume as an input for the calculation method based on material intensities. Since there is only available data regarding the volume of construction from the year 2000, the comparison will only be made for the factors proposed from this year, being those that are earlier left out of this study. The coefficients proposed by the

"*Building up approach for residential buildings based on age*" (see APPENDIX C) will be compared with those proposed by the "*Building up approach for residential buildings based on age and building type*" for residential buildings (see APPENDIX D). For all periods, significantly higher concrete, bricks and metals intensity coefficients are observed in the first approach.

A comparative analysis will then be made between the proposed MCIs for non-residential buildings. Since the data is only available from 2008, as in the previous case, the comparison will be made between the latest proposed coefficients. In the case of non-residential buildings, both approaches show higher intensities of concrete and metals than residential buildings, but a lower concentration of wood. In the category office and administration buildings, the proposed coefficients will be identical to those used in the case of institutional buildings. For industrial buildings (agricultural and farm buildings and non-farm agricultural buildings), there will be a lower proportion of concrete in comparison to those in the other types of buildings.

Then the comparison will be made between those coefficients used to determine the waste derived from construction, renovation and demolition activities. This comparison will be atypical in comparison to those carried out previously. This is because, as indicated above, it is not a usual comparison between two different methods, but rather a combination of the method proposed by Bergsdal, Bohne and Brattebø (2008), and the method proposed "*Bottom up approach based on age*" for predictions in MFH, and the method proposed by "*Bottom up approach based on age and building type*" for predictions in SFH.

As described previously, the method described will use the MCIs proposed by "*Bottom up approach based on age*", based on the premise that once these buildings are demolished, a waste output equal to the material input will be generated during the construction phase. The relation between the different construction and renovation coefficients with those of demolition extracted from Bergsdal, Bohne and Brattebø (2008), will be applied to those in the first method (see APPENDIX H).

As for Asbestos category, there is no generation of this material during the construction phase, being 0,23 for both MFH and SFH in the renovation phase. Also noteworthy is the significantly higher amount of gypsum waste material generated in construction and renovation activities than in demolition activities. The ratio will be 0,90 and 138,00 waste units under construction phase, respectively for SFH and MFH, for each unit under demolition phase. For the renovation activity, 1,75 and 244,00 will be generated. In the case of papers and plastics, a similar fact occurs. The ratios for the construction activity are 3,17 and 1,44 and 0,77 and 2,13 for the renovation activity, for concrete and bricks, waste generated in these two activities will be less significant compared to the demolition activity. Being 0,02 for both in construction, and 0,10 and 0,03 respectively in renovation

4.4 Statistical analysis and comparison of the results

Once the different methods have been applied and several sequences of results corresponding to the net added material stock per group of material have been obtained, it is necessary to make a comprehensive analysis of these results. This comparison is carried out in order to highlight any significant difference that may exist between the methods applied by comparing them with each other. This will be of vital importance in identifying methods that correctly characterize the annual flow of materials in the city of Hamburg.

Firstly, a statistical analysis has been carried out to check whether there are significant differences between different methods of calculating stock values for the same type of material over the same period. By using the ***T-Student tool*** two different sequences of values can be compared so that it can be determined whether statistically significant differences at a probability level of less than 0,05 exist. At the same time, another statistical analysis, ***the single factor ANOVA tool***, is applied when there are more than two sequences of values to compare. In the following subsections, different comparisons between the methods are applied.

- Comparison of bottom up approaches considering the volume of buildings

In this case, a comparison has been made regarding material flows added to the total stock of the city of Hamburg calculated on the basis of the methods set out in the building-up approach (age) and the method building-up approach (age, use and building type) respectively. The comparison is first made in general terms, considering mainly subcategories within the typologies: mineral, organic, and metallic. In addition, the overall sum of the quantities obtained for each year will be compared so as to obtain a global idea in terms of orders of magnitude. A more detailed and focused analysis of the various subcategories will then be carried out, so that it will be possible to obtain a more detailed idea of the differences between both methods.

First, in general terms, it is possible to conclude form the statistical analysis carried out through the ANOVA tool that there are no statistically significant differences between the results obtained annually by each of the two methods. When both sequences of values are compared by using the ANOVA Tool, the results do not show statistically significant differences. The notation of the ANOVA result has been as follows: "*F(1,36)=3,666, p<0,063*". From the analysis it is possible to conclude that, since the condition that the numerical value of *F* is strictly lower than the critical value of *F*, there are no statistically significant differences between the two sequences.

For the category of mineral materials (plaster, scree, mortar, concrete and masonry), observed in general terms, the notation of the ANOVA result will be as follows: "*F(1,36)=1,575, p<0,218" (obtained F smaller than calculated critical F)*, implying that no significant statistical differences were found when using the ANOVA tool. Furthermore, no significant differences have been determined for the category of organic materials, including these mainly wood, wood flooring and building boards. The notation of the ANOVA result has been as follows: "*F(1,36)=0,792, p<0,379*".

In the case of metallic materials, statistically significant differences have been determined between the two methods. These materials include both iron and steel used in construction, aluminum, as well as copper elements. It is possible to observe that the annual difference in stock of added net material is significantly higher in the case of the sequence of results obtained by the building-up approach (age) method than that of the building-up approach (age, use and building type). This difference is qualitatively appreciable, since for almost all the values in the sequences of results, the value obtained by the second method is 51,7% of the first based on the MCIs used. In this case, the notation of the ANOVA result will be as follows: "*F(1,36)=26,302, p<1,013E-05*".

As explained above, a series of statistical analyses will be carried out below for the most representative subcategories so that it will be possible to highlight the differences between the methods, which will be discussed further. With regards to the use of concrete, it is possible to determine that the method based on the building-up approach (age) study envisages a more intensive use of this material than in the case of the building-up approach (age, use and building type). The use of concrete regarding the MCIs suggested by the building-up approach (age and building type) a are approximately 72,3% of those suggested by the other method. The notation of the ANOVA result will be as follows: "*F(1,36)=7,228, p<0,011*".

Regarding the masonry category, the evidence based on the ANOVA analysis used reject the hypothesis that there is statistically significant evidence. Quantitatively, the average difference between the two data sequences determines that the material intensity covered by the building-up approach (base) method is of the order of 87,8 % higher than that covered by the second method. The notation of the ANOVA result been as follows: "*F(1,36)=1,171, p<0,286*".

The building-up approach (age) beholds two categories (insulation materials and roof covering) which are impossible to frame in a precise material category. This is due to the multiplicity of materials of which this series of elements can consist.

- Comparison between building-up approach (age) (volume) and building-up approach (age) (available floor space)

In this case, a comparison will be made between the sequences of results obtained using the coefficients proposed by building-up approach (age), taking available floor space or volume respectively as starting data. The statistical analysis is directly applicable as both methods consider the same material groups, differing only in the material intensities considered. As highlighted above, only data for the volume of construction between 2000 and 2018 are provided in the federal records.

Regarding the material group concerning plaster screen and mortar, there is high evidence not to rule out the null hypothesis considered, so it is concluded that there are no significant statistical differences between the two data sequences. The notation of the ANOVA result will be as follows: "*F(1,36)=0,029, p<0,958"*. Being the obtained *F* value significantly lower than the critical value of *F* (4,113), supporting the non-denial of the previous hypotheses.

Performing the analogous analysis for the concrete stock in the city of Hamburg, it is possible to conclude that, there are no statistically significant differences between the two sequences either. The notation of the ANOVA result will be as follows: "*F(1,36)=0,030, p<0,957".* In the case of masonry, it is also concluded that there are no statistically significant differences between the two sequences. The notation of the ANOVA result will be as follows: "*F(1,36)=0,015, p<0,969".*

For construction boards, no significant differences have been detected either, even though the probability of rejecting the null hypothesis is not as high as in the previous cases. The notation of the ANOVA result will be as follows: "*F(1,36)=0,580, p<0,451".* In the case of wood and engineered timber, the notation of the ANOVA result will be as follows: "*F(1,36)=5,467E-05, p<0,994".* With a high probability of not rejecting the hypothesis that there are no statistical differences.

With regards to roof-covering and flooring materials, the notation of the ANOVA result will be respectively: "*F(1,36)=0,580, p<0,451" and* "*F(1,36)=0,229, p<0,635".* Concluding that in both cases there are no statistically significant differences. In turn, for the group of materials framed within construction fills, the notation of the ANOVA result is respectively: "*F(1,36)=0,0004, p<0,985".* Also making it impossible to reject the null hypothesis with a high probability.

- Comparison between the building-up approach (age and building type) and building-up approach (age) (volume)

In this section, a statistical comparison will be made between the different material categories covered by the methods. These methods, as indicated above, are based on the available floor space in order to determine the material stock. As in the previous case, a statistical comparison will be made between the different categories of materials considered when evaluating the total stock of materials in dwellings. The data presented for the net added floor space starts in the year 1918 and ends with the last annual report of the city of Hamburg for the year 2018. The categories referred to, in a similar way to the previous case, will be wood-based materials, ceramic and bricks, mineral-binding materials, stone and aggregates and several miscellaneous.

For the category of concrete, the differences obtained after the application of the ANOVA toll for the sequence of results between 1918 and 2018 indicate, with a high probability, the impossibility of rejecting the hypothesis that there are statistically significant differences between both methods. The notation of the ANOVA result will be as follows: "*F(1,68)=0,126, p<0,723*". Being the obtained *F* value significantly lower than the critical value of *F* (3,981), supporting the non-denial of the previous hypotheses.

With regard to the category of wood-based materials (including wood flooring and building boards), there are also statistically significant differences between both methods. The notation of the ANOVA result will be as follows: "*F(1,68)=0,0046, p<0,946*". Being the obtained *F* value significantly lower than the critical value of *F* (3,981), supporting the non-denial of the previous hypotheses.

5 CONCLUSSION

As highlighted above, the CDW problem accounts for approximately 25% to 30% of the total flow of waste material in the European Union. In turn, the target set of a 70% recycling rate is far from being achieved in many countries. Major efforts are currently being made by both public and private initiatives to increase recycling rates of building materials. To this end, a series of strategies have been identified for the efficient management of this waste throughout its useful life and subsequent reuse. Firstly, the development of a database of materials, including the different properties of these, is proposed to assist experts in pre-demolition audits in order to improve the management of waste flows. Along with this, further work should be done in order to implement a unified, specific standardization model for these materials so as to reduce misconceptions about their use. At the same time, efforts have been made to create commercial exchange mechanisms for these materials, so as to improve their competitiveness in terms of both cost and availability for the user.

It should be noted that in order to promote a circular economy, in particular in the construction sector, a global representation of the current state of residential and non-residential stock in the city of Hamburg is necessary. This requires more detailed data on construction activity from the competent authorities, since in most cases there are currently no disaggregated data that would allow models based on material intensities to be faithfully applied.

Through estimates made by means of bottom-up approaches based on age and on age and type of building respectively, for the years 1901-2019 a significant concentration of materials added between 1949 and 1978 has been observed. There has been a significant increase in the amount of concrete used due to the change in construction techniques employed in the period of reconstruction of the city during the so-called "German Economic Miracle”. The input of concrete and ceramic materials in this period was 30.000.000 tonnes and 10.000.000 tonnes respectively. As these materials have the greatest potential for recycling, it is necessary to carry out a specific analysis of them. This study will be particularly important for MFH, since based on the results obtained, the percentage of concrete represents values higher than 60% of the total input against 20% in SFH. Considering an average life of residential buildings in Germany equal to 80 years, it is crucial to study in detail the input in this period in order to obtain detailed and realistic predictions for the 2040-time horizon.

In comparison with the residential stock, the lower percentage of input of traditional materials used in the construction of non-residential buildings should also be noted. Once again, the change of trend in construction techniques is postulated as the explanation for this fact since design on metallic structures, more functional and aesthetic, is common among the latter.

When selecting MCIs that faithfully represent the material input trend in the city of Hamburg, it is necessary to take into account the particularities of the prevailing building style in Hamburg. By comparing the results of the age-based bottom-up approach with those based on age and building-type, a difference is observed between the total of 110.000.000 tons added as a result in the first one, to 65.000.000 in the second one in the period between 1901 and 2019. Being the quantities of concrete obtained practically identical for both approaches, with a critical view of the data, it is possible to affirm that the second approach makes an insufficient quantification of the intensities of ceramic materials. Because of the importance that ceramic materials have traditionally had in the Hamburg building activity necessary to consider this fact when implementing the analysis. Therefore, it is concluded that, in order to obtain reliable results, it is necessary to use ICMs based on population samples that are geographically close and whose characteristics are similar to the study population.

Regarding the building-up approaches based on volume of construction as input it is possible to conclude that, having a smaller sequence of data available (2000 to 2019 in most cases), and the coefficients being more similar to each other than in floor-size - based approaches, fewer differences are obtained between methods. This fact has been contrasted both qualitatively through the comparison of results, and quantitatively through the ANOVA analysis, for which no statistically significant differences have been found when comparing the different approaches.

Regarding the predictions for the waste material flows expected from the year 2020, with a critical view of the results, a great management effort will be necessary due to the imminent need to demolish the buildings built after 1949, at the end of their lifespan. In the case of renovation activity, a significant intensification is expected in the period between 2025 and 2030, which in turn will generate an increase in the amount of waste generated.

The need to manage the waste derived from construction activity highlights the need for new ways of modeling the housing stock of a city with a view to making the management of waste flows more efficient. It should be noted that models based on foor space or on volume as input are useful when making estimates regarding trend changes in the stock of material, observing trends and making predictions. However, from this study the need to implement methods and tools capable of identifying and analyzing the different elements that make up the residential and non-residential stock of a certain area is extracted. Tools such as GIS will be crucial when creating detailed models of a certain area and databases that allow mapping and performing individualized analysis that allow managing waste in a more faithful and efficient way.

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7 APPENDIX

APPENDIX A. Residential buildings in total by the year 2002

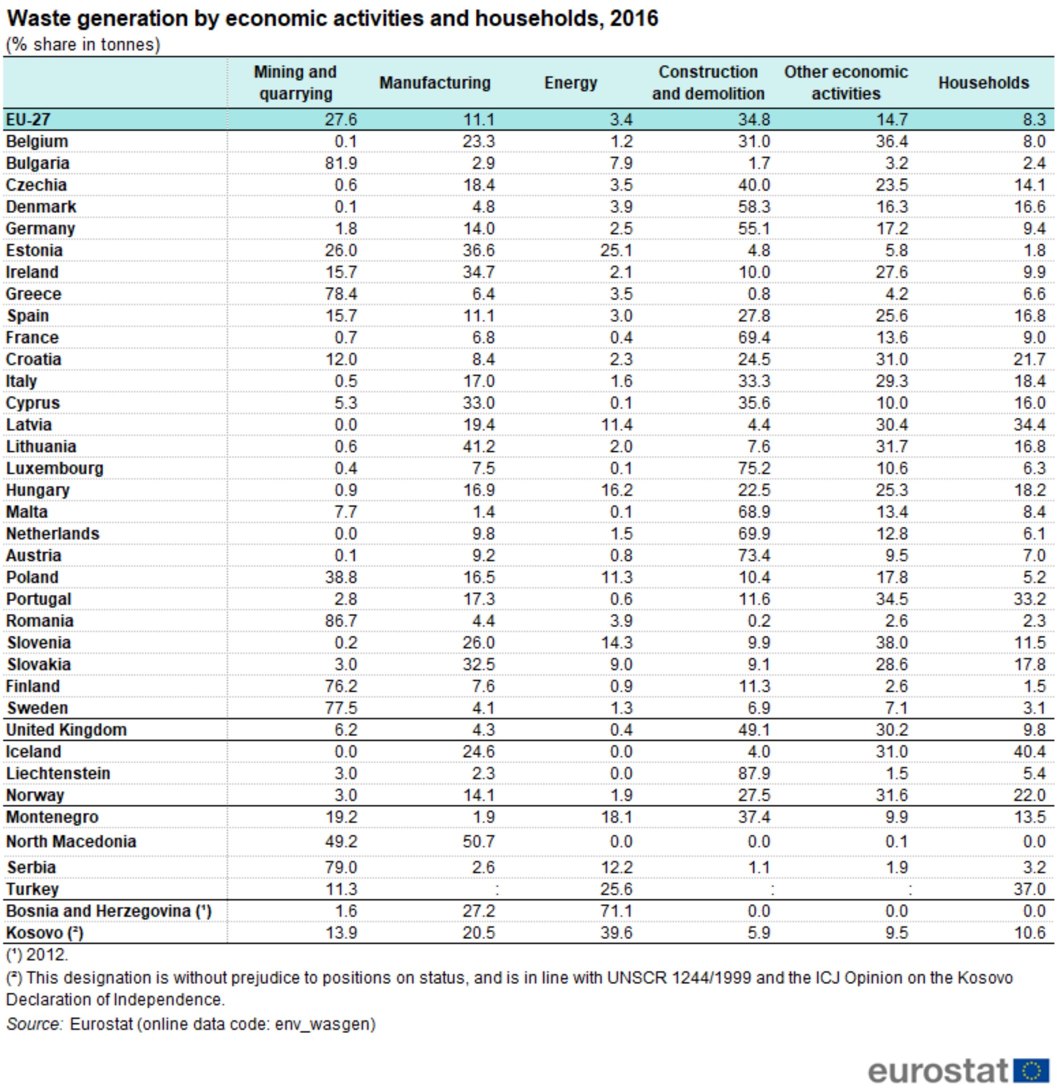
Residential buildings in total by the year 2002

Year	Number of apartments built per period	Number of apartments in total from 1900	Available living floor space in residential buildings (m2)	Added living floor space in residential buildings (m2)
Built from…to	1000	1000		
until 1900	48	48	3417600	3417600*
1901-1918	69	117	8330400	4912800
1919-1948	118	235	16732000	8401600
1949-1978	491	726	51691200	34959200
1979-1986	58	784	55820800	4129600
1987-1990	13	797	56746400	925600
1991-2000	51	848	60377600	3631200
2001 and later	5	853	60733600	356000

*There is a lack of information for the buildings before 1900

Note. Reprinted from *Statistisches Jahrbuch Hamburg 2005/2006*, n. d.

APPENDIX B. Waste generation by economic activities and households, 2016



Waste generation by economic activities and households, 2016

(% share in tonnes)

	Mining and quarrying	Manufacturing	Energy	Construction and demolition	Other economic activities	Households
EU-27	27.6	11.1	3.4	34.8	14.7	8.3
Belgium	0.1	23.3	1.2	31.0	36.4	8.0
Bulgaria	81.9	2.9	7.9	1.7	3.2	2.4
Czechia	0.6	18.4	3.5	40.0	23.5	14.1
Denmark	0.1	4.8	3.9	58.3	16.3	16.6
Germany	1.8	14.0	2.5	55.1	17.2	9.4
Estonia	26.0	36.6	25.1	4.8	5.8	1.8
Ireland	15.7	34.7	2.1	10.0	27.6	9.9
Greece	78.4	6.4	3.5	0.8	4.2	6.6
Spain	15.7	11.1	3.0	27.8	25.6	16.8
France	0.7	6.8	0.4	69.4	13.6	9.0
Croatia	12.0	8.4	2.3	24.5	31.0	21.7
Italy	0.5	17.0	1.6	33.3	29.3	18.4
Cyprus	5.3	33.0	0.1	35.6	10.0	16.0
Latvia	0.0	19.4	11.4	4.4	30.4	34.4
Lithuania	0.6	41.2	2.0	7.6	31.7	16.8
Luxembourg	0.4	7.5	0.1	75.2	10.6	6.3
Hungary	0.9	16.9	16.2	22.5	25.3	18.2
Malta	7.7	1.4	0.1	68.9	13.4	8.4
Netherlands	0.0	9.8	1.5	69.9	12.8	6.1
Austria	0.1	9.2	0.8	73.4	9.5	7.0
Poland	38.8	16.5	11.3	10.4	17.8	5.2
Portugal	2.8	17.3	0.6	11.6	34.5	33.2
Romania	86.7	4.4	3.9	0.2	2.6	2.3
Slovenia	0.2	26.0	14.3	9.9	38.0	11.5
Slovakia	3.0	32.5	9.0	9.1	28.6	17.8
Finland	76.2	7.6	0.9	11.3	2.6	1.5
Sweden	77.5	4.1	1.3	6.9	7.1	3.1
United Kingdom	6.2	4.3	0.4	49.1	30.2	9.8
Iceland	0.0	24.6	0.0	4.0	31.0	40.4
Liechtenstein	3.0	2.3	0.0	87.9	1.5	5.4
Norway	3.0	14.1	1.9	27.5	31.6	22.0
Montenegro	19.2	1.9	18.1	37.4	9.9	13.5
North Macedonia	49.2	50.7	0.0	0.0	0.1	0.0
Serbia	79.0	2.6	12.2	1.1	1.9	3.2
Turkey	11.3	:	25.6	:	:	37.0
Bosnia and Herzegovina (1)	1.6	27.2	71.1	0.0	0.0	0.0
Kosovo (2)	13.9	20.5	39.6	5.9	9.5	10.6

(1) 2012.

(2) This designation is without prejudice to positions on status, and is in line with UNSCR 1244/1999 and the ICJ Opinion on the Kosovo Declaration of Independence.

Source: Eurostat (online data code: env_wasgen)

eurostat

Note. Reprinted from *Eurostat,* 2016.

APPENDIX C. Hamburg Household description for the period between 1970 and 2018

Year	Number of new residential buildings	Number of new apartments in residential and non-residential buildings	With ... rooms				New-built living space in residential and non-residential buildings	Average living space per apartment
			1-2	3	4	5 and more room		
1970	1830	12087	2353	2686	4243	2805	846100	70
1975	1307	9104	1500	1837	2771	2996	710300	78
1980	1985	5636	691	1215	1297	2433	498700	88,5
1985	1409	4897	623	1107	1361	1806	401600	82
1990	1331	2826	315	522	603	1386	255800	90,5
1995	1648	9750	2037	3080	2599	2034	693600	71,1
2000	2095	6502	627	1345	1962	2568	571410	87,9
2001	1541	5054	299	1168	1704	1883	482590	95,5
2002	1532	3711	269	603	828	2011	388660	104,7
2003	1581	3862	237	627	986	2012	402060	104,1
2004	1699	3893	209	638	1019	2027	417390	107,2
2005	1442	3251	321	488	731	1711	350060	107,7
2006	1882	4278	523	826	826	2103	458880	107,3
2007	1318	3173	408	610	702	1453	355800	112,1
2008	1527	3758	452	698	986	1622	407130	108,3
2009	1190	3587	402	807	875	1503	384140	107,1
2010	1286	3520	403	741	837	1539	374490	106,4
2011	1378	3729	469	655	920	1685	398830	107
2012	1246	3793	591	963	806	1433	406140	107,1
2013	1906	6407	1031	1651	1461	2264	653850	102,1
2014	1356	6974	1734	1986	1574	1680	619790	88,9
2015	1760	8521	2183	2535	1883	1920	756690	88,8
2016	1438	7722	2289	2412	1636	1385	650210	84,2
2017	1700	7920	2396	2323	1512	1689	671960	84,8
2018	1882	10674	3907	3019	1890	1858	849430	79,6

Note. Reprinted from *Statistisches Jahrbuch Hamburg 2019*, n. d.

APPENDIX D. Material composition indicators (MCIs) for residential buildings differentiated according to product groups in tonnes per m^2 floor space and tonnes per m^3 gross volume.

	1918		1919–48		1949–78		1979–90		1991–2010	
Product groups	t/m²	t/m³	t/m²	t/m³	t/m²	t/m³	t/m²	t/m³	t/m²	t/m³
Plaster, scree, mortar	0,664	0,106	0,639	0,115	0,360	0,078	0,225	0,052	0,303	0,069
Concrete	0,161	0,026	0,389	0,070	1,146	0,250	1,336	0,310	0,962	0,219
Masonry	1,470	0,234	1,219	0,219	0,447	0,098	0,299	0,069	0,669	0,153
Building boards	0,000	0,000	0,000	0,000	0,005	0,001	0,012	0,003	0,011	0,002
Wood, engineered timber	0,098	0,016	0,030	0,005	0,012	0,003	0,009	0,002	0,026	0,006
Insulation materials	0,012	0,002	0,007	0,001	0,020	0,004	0,012	0,003	0,019	0,004
Roof covering	0,016	0,003	0,009	0,002	0,004	0,001	0,003	0,001	0,011	0,002
Floorings, damp-proofing	0,001	0,000	0,004	0,001	0,006	0,001	0,006	0,001	0,005	0,001
Other materials, fills	0,390	0,062	0,379	0,068	0,071	0,016	0,071	0,017	0,100	0,023
Metals	0,002	0,000	0,067	0,012	0,116	0,025	0,152	0,035	0,126	0,029
TOTAL	2,815	0,447	2,742	0,493	2,187	0,477	2,124	0,493	2,231	0,509

Note. Reprinted from Ortlepp et al., 2018.

APPENDIX E. Material intensity coefficients for the two residential building types for four age classes and various material categories.

Residential type	Age class	Wood-based material	SD	Ceramic and bricks	SD	Mineral-binding materials	SD	Stone and aggregates	SD	Iron and steel	SD	Miscellaneous	SD	Total	SD
		t/m2													
Single-family	**Before 1930**	0,199	0,009	0,033	0,000	0,119	0,000	0,730	0,431	0,003	0,000	0,024	0,000	1,108	0,240
	1931-1950	0,120	0,049	0,059	0,000	0,476	0,160	0,075	0,000	0,059	0,000	0,081	0,000	0,869	0,198
	1951-1980	0,070	0,000	0,053	0,000	0,492	0,210	0,000	0,000	0,107	0,040	0,051	0,000	0,772	0,304
	After 1981	0,069	0,000	0,035	0,000	0,343	0,084	0,000	0,000	0,065	0,000	0,091	0,018	0,602	0,125
Multi-family	**Before 1930**	0,155	0,000	0,624	0,487	0,204	0,000	0,259	0,194	0,051	0,000	0,066	0,000	1,358	0,473
	1931-1950	0,033	0,000	0,312	0,308	0,774	0,173	0,013	0,000	0,141	0,000	0,114	0,000	1,387	0,256
	1951-1980	0,019	0,000	0,043	0,000	0,965	0,163	0,012	0,000	0,171	0,092	0,021	0,000	1,230	0,135
	After 1981	0,034	0,000	0,007	0,000	0,788	0,300	0,000	0,000	0,317	0,148	0,062	0,000	1,206	0,187

Note. Reprinted from Gontia et al., 2020, p.

APPENDIX F. Per capita figures on the materials present in buildings in Vienna (rounded to two significant digits)

	t/cap	t	Percentage
Mineral	200	348200000	95,79%
Concrete	83	144503000	39,75%
Bricks	70	121870000	33,52%
Mortar/plaster	29	50489000	13,89%
Mineral fill	7,8	13579800	3,74%
Slag fill	3,4	5919400	1,63%
Gravel/sand	2,7	4700700	1,29%
Plaster boards/gypsum	0,74	1288340	0,35%
Natural stone	0,72	1253520	0,34%
Foamed clay bricks	0,71	1236110	0,34%
Ceramics	0,42	731220	0,20%
(Cement) asbestos	0,34	591940	0,16%
Glass	0,22	383020	0,11%
Mineral wool	0,21	365610	0,10%
Mineral wool boards	0,017	29597	0,01%

	t/cap	t	Percentage
Organic	5,5	9575500	2,63%
Wood	4	6964000	1,92%
Various plastics	0,35	609350	0,17%
Bitumen	0,22	383020	0,11%
Carpet	0,19	330790	0,09%
Heraklit	0,16	278560	0,08%
Asphalt	0,13	226330	0,06%
PVC	0,10	174100	0,05%
Polystyrene	0,076	132316	0,04%
Paper/cardboard	0,059	102719	0,03%
Laminate	0,029	50489	0,01%
Linoleum	0,014	24374	0,01%

	t/cap	t	Percentage
Metal	3,3	5745300	1,58%
Iron/steel	3,2	5571200	1,53%
Aluminium	0,045	78345	0,02%
Copper	0,031	53971	0,01%
Lead	0,0023	4004,3	0,00%
Brass	0,0012	2089,2	0,00%

APPENDIX F (a). Empirical waste generation factors and material composition (kg/m^2)

	Construction			Renovation			Demolition		
COMPOSITION	Small	Large	Other	Small	Large	Other	Small	Large	Other
Asbestos	0,00	0,00	0,00	0,50	0,50	0,50	2,14	2,14	2,14
Hazardous	0,07	0,07	0,07	0,03	0,03	0,03	0,40	0,42	0,23
Concrete/bricks	6,50	19,11	17,52	40,40	30,45	18,77	394,30	1012,46	519,34
Gypsum	3,04	1,38	0,80	5,90	2,44	2,30	3,37	0,01	0,31
Glass	0,24	0,12	0,00	0,29	0,29	0,29	2,59	0,44	0,20
Insulation/EPS	1,20	0,21	0,10	0,62	0,14	0,10	1,69	0,00	0,09
Metals	0,11	0,48	0,79	0,38	4,06	6,05	4,45	7,70	45,31
Paper/Plastics	2,92	0,46	0,26	0,71	0,68	0,14	0,92	0,32	2,57
Wood	5,68	2,75	4,05	37,94	8,06	2,30	105,84	48,55	17,09
Unknown	9,60	6,19	7,91	2,70	13,48	2,70	59,02	31,21	14,67
Total	29,36	30,77	31,50	89,47	60,13	33,18	574,72	1103,25	601,95

Note. Reprinted from Bergsdal et al., 2008

APPENDIX F (b). Assumed Waste Generation Coefficients based on activity rate criteria for MFH

	Construction	Renovation		Demolition
	1991 and after	1979-90	1991-2010	1949-78
Product groups	t/m2fs	t/m2fs		t/m2fs
Plaster, scree, mortar	0,001	0,002	0,002	0,360
Concrete	0,022	0,040	0,029	1,146
Masonry	0,008	0,009	0,020	0,447
Building boards	0,000	0,002	0,002	0,005
Wood, engineered timber	0,001	0,001	0,004	0,012
Insulation materials	-	-	-	0,020
Roof covering	0,000	0,000	0,000	0,004
Floorings, damp-proofing	0,000	0,000	0,000	0,006
Other materials, fills	0,000	0,000	0,000	0,071
Metals	0,007	0,080	0,066	0,116

APPENDIX F (c). Assumed Waste Generation Coefficients based on activity rate criteria for SFH

	Construction	Renovation	Demolition
	After 1981	After 1981	1951-1980
Product groups	t/m2fs	t/m2fs	t/m2fs
Wood-based materials	0,000	0,016	0,070
Ceramic and bricks	0,001	0,005	0,053
Mineral-binding materials	0,008	0,050	0,492
Stone and aggregates	0,000	0,000	0,000
Iron and Steel	0,003	0,009	0,107

APPENDIX F(d). Rate between construction and renovation activities and demolition activity based in coefficients proposed by Bergsdal, Bohne and Brattebø (2008)

	Construction		Renovation	
COMPOSITION	**Small**	**Large**	**Small**	**Large**
Asbestos	0,00	0,00	0,23	0,23
Hazardous	0,18	0,17	0,08	0,07
Concrete/bricks	0,02	0,02	0,10	0,03
Gypsum	0,90	138,00	1,75	244,00
Glass	0,09	0,27	0,11	0,66
Insulation/EPS	-	-	-	-
Metals	0,02	0,06	0,09	0,53
Paper/Plastics	3,17	1,44	0,77	2,13
Wood	0,05	0,06	0,36	0,17
Unknown	0,16	0,20	0,05	0,43

	Construction	Renovation
Product groups	**MFH**	**MFH**
Plaster, screed, mortar	138,00	244,00
Concrete	0,02	0,03
Masonry	0,02	0,03
Building boards	0,06	0,17
Wood, engineered timber	0,06	0,17
Insulation materials	-	-
Roof covering	0,02	0,03
Metals	0,06	0,53