
Palác Morava, Malinovského náměstí (2022, Foto Studio Flusser)

Master Thesis

Material stock of buildings in Brno
Towards circularity in the construction and demolition industry

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June 12
2023

Industrial Ecology
Leiden University and Delft University of Technology

Summary

The extraction and use of virgin materials cause significant environmental impacts. Both scientists and governments are trying to find ways to decrease our dependency on virgin materials and shift towards more circular practices to use secondary materials. The built environment represents a large stock of in-use materials called urban mine, which could be potentially used in the future. This requires prospection – understanding of the location and quantities of these materials, and exploration – understanding the characteristics and more granular information about the material stock – of the anthropogenic material stock. The latter is the object of this thesis research project.

This thesis presents an investigation of the current stock of concrete, bricks, and mortar in buildings in the urban mine of Brno (Czech Republic), as these are the major material stocks in buildings. The city of Brno represents a case study from an area of Europe that has not been studied in such way before. This investigation utilizes the bottom-up GIS approach, which allows for high differentiation of data by estimating material stocks on the per-building level. This is based on material intensities (quantities of materials per unit of space) based on the different building functions and construction years and multiplication with the total floor areas of the buildings. The result of such study provides material stocks per building, total values per whole study area, and spatial distribution of these materials.

The research uses the geographical approach for its research design, which comprises of 5 steps: ask, acquire, examine, analyse, and act. First step defines the necessary data input; second, the data are collected, which is followed by the third step, where data are reviewed, processed, and managed. Once data are prepared, various data analysis operations are conducted, so that data outputs can be produced in the fourth step, in form of tables, graphs and maps. In the last step, results are interpreted and translated into recommendations.

In this research, a GIS software called ArcGIS is used to store, manage, and analyse data, followed by producing results. Necessary data inputs for this study include building objects (geo location), surface area (m^2), number of floors (#), construction period, building function (residential and non-residential) and material intensity (kg/m^2). All of these data were collected from public data services of data.Brno and Architect Office of Brno, except the material intensity data. The material intensity data were not found and were therefore substituted with a dataset based on a study of the material stock in Vienna, Austria.

Aside from the GIS analysis, relevant sources and literature were explored to gain general understanding of the circular construction and demolition industry as to its general characteristics, actors, challenges towards transition, and trends. This knowledge was used to inform and motivate how could the results of the GIS analysis can be used and whom should they serve. It was recognized that GIS analysis on the presented case can be applied for improvements of the reuse and recycle aspects of circular C&D, and that the insights are mostly relevant for government bodies, local authorities, demolition companies and waste processors. Additionally, the environment of circular C&D in Czech Republic in terms of existing frameworks, plans and current developments.

The results show the total material stock of concrete, bricks, and mortar, differentiated by building function, construction period, average building compositions, and combination of these. Additionally, the results generated maps that show spatial distribution of the buildings by building function and construction period, but more importantly spatial distribution of the material stocks of concrete, bricks, and mortar.

When interpreting the results, the biggest potential urban mine in the future is presented by building cohorts from periods 1919-1946 and 1947-1977, as these building might be reaching the end-of-life stage of their lifecycle. Buildings from the 1919-1946 are characterized as consisting mainly from brick and mortar, but also with relevant amounts of concrete. They represent the second most numerous stock in terms of number of buildings from all the cohorts and they also contain the second highest material stock in terms of mass. The are located mainly in the district *Brno-Střed, Žabovřesky, Královo Pole, Brno-Sever, Židenice,* and *Černovice.*

Buildings from the 1947-1977 are largely characterictis for prefabricated panel houses constructed during the communist era in Czech Republic. The material stock of this period is both the most numerous in terms of buildings and in total mass of material, which are dominated by concrete, however about third of the material stock consists of bricks and mortar. These buildings are present especially in panel house estates in districts such as *Starý* and *Nový Lískovec, Bohunice, Kohoutovice, Bystrc, Komín, Slatina, Líšeň, Vinohrady, Řečkovice* and *Lesná,* and additionally in form of extension of districts such as *Žabovřesky* and *Královo Pole*. For both of these cohorts, the future availability of the material stock as an urban mine depends largely on their survivability (age and level of maintenance, which is outside of the scope of this research). The mass per capita in this case is 146 ton per capita, which matches the results of other case studies focusing on developed countries, especially in the Western Europe.

The total material stock of these two cohorts is estimated as shown below in table A.

Table A Material stock of concrete, bricks and mortar (t) buildings from 1919-1946 and 1947-1977

	1919-1946	1947-1977
Concrete (t)	5.725.836	14.335.884
Bricks (t)	5.412.891	5.646.339
Mortar (t)	1.963.913	2.002.239

Government, municipalities, demolition companies and waste sorting, treatment and processing companies are encouraged to collaborate to collect and share reliable and relevant data in order to manage future waste material outflows, such as by deciding on the location and capacities of future waste treatment facilities. Pilot projects are great for all actors to gain knowledge and understanding of challenges and barriers, that can be addressed before scaling up. Markets for secondary materials need to be promoted and facilitated by government and municipalities, while demolition and waste processors need to be incentivized to choose for recycling and reuse of waste materials. Governments must provide clear rules and regulations that support recycling and reuse, while providing indicators and targets for circular C&D. Also, they need to stipulate or incentivize systematic data collection, and conduct case studies on material intensities for different typologies of buildings in Czech Republic. Brno municipality should take the results of this study further by projecting future waste outflows and expanding the inventory of material stock with other materials than just concrete, bricks and mortar. They should work closely with local and regional companies to remove barriers and help them planning for and meeting national goals for recycling and reuse. Demolition companies and waste processors need to provide data and communicate their challenges to authorities so that suitable regulations can be drawn up. These companies should employ innovative business models, novel technical solutions, and make use of governmental incentives for adapting circular practices.

List of abbreviations

GIS – Geographical Information Systems

C&D – Construction and Demolition

CE – Circular Economy

LCA – Life Cycle Assessment

MFA – Material Flow Analysis

MI – material intensity

Acknowledgements
This thesis has been written solely by me, Karel Jeniš, for the purpose of graduation from the MSc. Industrial Ecology at Leiden University and Delft University of Technology.

Supervision
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Word of thanks
I would like to thank the first supervisor, Tomer Fishman, and the second supervisor, Jaco Quist, for guidance, support and insightful comments provided during the process of the thesis writing. Secondly, I would like to thank Maarten van 't Zelfde for consultation and advice regarding use of the ArcGIS software. Finally, I would like to thank all the parties that provided data for this research project, namely the Architect Office in Brno, and data.Brno, without which this research would not be possible.

1. Chapter: Introduction

1.1 Problem Background

The industrial revolution marked the beginning of the period now widely coined as the Anthropocene. During this period humankind expanded its influence on the environment above-all due to the growing population and industrialization (Crutzen, 2002) and related growth in demand among others for food, fresh water, fuel, industrial and construction minerals (Behrens et al., 2007). This accelerated the pressures on various earth systems triggering global warming and other environmental issues, most prominently through the emission of carbon dioxide and other greenhouse gases, but also in terms of ocean acidification, forest loss, toxicity, or nitrogen depositions just to name a few (Steffen et al., 2015). Many of these issues are traced back to resource extraction and use caused by emissions and waste discharge (Haberl et al., 2017).

Resources obtained from the natural environment serve to build and maintain societies and national economies (Fischer-Kowalski et al., 2011). These materials are either used up in the short term, such as biomass or fuels, while others are ‘in-use’ and ‘stored’ in society for extended periods of time, which are referred to as material stocks (Miatto et al., 2019). Material stocks consist mostly of non-metallic and metallic minerals, which are essential to society as they provide means for humans to satisfy their needs, whether they are directly consumed or used to produce other resources (Haberl et al., 2017).

1.2 Problem Description

Each of the described material categories pose challenges for society and require attention, however, the evidence for the magnitude of the building sector regarding resource extraction and use is overwhelming. The building sector dominates the in-use material stocks with materials such as concrete, aggregates and bricks as can be seen in figure 1.1 (Krausmann et al., 2017) and construction materials in general represent the largest inflow into societies second to water (Krausmann et al., 2009). Most resources in this sector are non-renewable, and some of them are in short supply (Gordon et al., 2006), while their environmental impacts caused by extraction, processing, use, and disposal are significant (IEA, 2019). Additionally, construction and demolition (C&D) waste represents the largest solid waste flow and ranks among the ones with the lowest recycling rates (Krausmann et al., 2017). The construction sector has been included in the target areas in the EU’s circular economy roadmap as part of the Green Deal especially due to the environmental impacts caused by the production of primary resources (EU, 2020). The idea to decouple economic growth from the use of primary resources (UNEP, 2011) has motivated a crucial strategy to ramp up secondary resource use (EU, 2011), which requires in the first place a better understanding of the material stock itself.

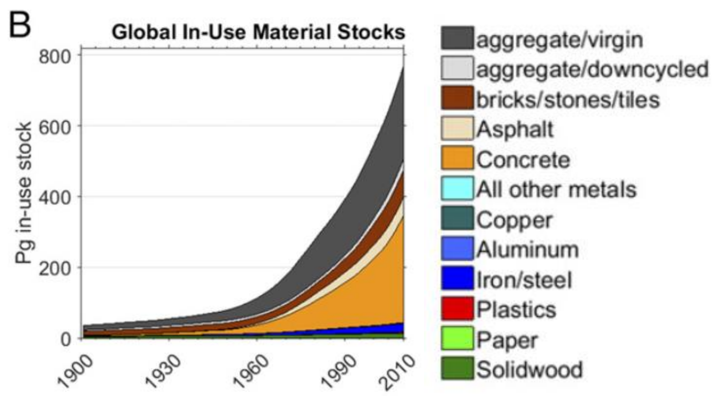


Figure 1.1 Global In-Use Material Stocks (Krausmann et al., 2017)

1.3 Research gap

Materials are vastly present in our societies and their potential for secondary use is currently examined in the field of industrial ecology and other environmental and technical disciplines (Cossu & Williams, 2015). Where other disciplines study how specific materials can be extracted and reused on a mechanical, chemical, and biological level, industrial ecology studies where these materials are stored, at what quantities, and what characteristics these material stocks have (Tanikawa & Hashimoto, 2009). In this domain, attention is given to studying existing accounts, in- and out-flows of these materials, and interpreting the results in order to inform policies and future scenarios. While various methods for analysing secondary materials exist, there is a gap in terms of characterizing the material stocks across different locations (Mastrucci et al., 2017). The gap that industrial ecology tries to address can be expressed with the following questions:

- What are the current stocks of materials and expected future outflows of these materials?
- Where are they located and at what quantities?
- What targets should and can be set on a societal level for recycling and reuse rates?
- How to make informed policy decision for improving the use of secondary materials on a larger scale?

This research gap is location-sensitive because unlike technical characteristics of materials that are universal, the characteristics of material stocks differ per location due to relatively different use materials, compositions, and metabolism of the stocks (Miatto et al., 2019). For that reason, material stocks are studied at different locations often with the use of case studies, so that the policy recommendations can be drawn up in the specific geographical, economic, and political context (Mastrucci et al., 2017). The review of various case studies is discussed in the section 2.1.5. Greater number of case studies also allows for comparisons across different material stocks and regions, for a better understanding of different socio-economic systems. Furthermore, one can focus on different material stocks, such as buildings, infrastructure or other built environment elements, such as waterways, pipelines, etc.

Such research gap can be addressed with a case study focusing on two aspects:

1) Material stocks of a specific type and location
2) Policy recommendations based on the results of the material stock investigation

In the following sections, a case study is selected for this graduation research project focusing on material stock of construction materials. This is based on the review of contemporary methods and other case studies, which are discussed in the section 2.1.

1.4 Case study selection – Brno, Czech Republic

Based on the review of existing case studies and associated literature, the case study for this thesis research uses a bottom-up GIS approach to estimate the material stock of a city from a country that has not been covered in other case studies. This method utilizes geographical data of construction objects and literature review of used materials to calculate the amount of construction materials in a bottom-up manner, meaning from individual objects to a total account of materials, as discussed generally in Chapter 2 and specifically for this case in Chapter 3. Different stocks can be investigated, however, most of the contemporary research is conducted on material stocks in buildings. The focus of this case study is therefore on the structural building materials such as concrete, bricks, and mortar, which are the largest stocks of material for similar studies based on review of other studies.

Sometimes, non-structural materials such as glass, aluminium or copper are also considered as they have generally more potential for circularity. The difference between structural and non-structural materials is that structural materials are embedded in load-bearing structures of buildings, while non-structural materials, which are used for instance for windows or wiring, are replaced more regularly without the building needing to be demolished. However, this case study focuses only on the structural materials due to reasons of data availability for such materials as discussed further in the Chapter 3.

For this thesis, a case study on the city of Brno, in the Czech Republic, is selected for the following reasons.

Relevancy for current research

Countries in the Eastern Europe have not been covered in other case studies as discovered during the review of the past case studies, which would enrich the current research in material stocks in buildings in this region. Czech Republic is a post-communist country, in which urban planning was heavily influenced by the centralized planning of the communist regime, and it could yield interesting insights into material stock and spatial distribution of the materials in question, as a useful comparison to more developed Western-European countries, for which case studies exist.

Suitability of the location

The country has digitalized land register tools such as cadaster and some cities use public geodata, which gave a head start for the use of the GIS bottom-up approach. Since I come from Czech Republic, I was able to read Czech literature, websites and other documentation. It also enabled me to contact various actors with request for data and increased the chance of receiving a reply from them.

Scoping

The choice for the city of Brno is motivated by the fact that it is comparable in size to studies that have used the same approach, such as Vienna (Kleemann et al., 2017) or Padua (Miatto et al., 2019). The city itself is the second biggest city in the Czech Republic, characteristic with a historical centre, numerous industrial zones, relatively newly built suburbs and recently growing technological park. It offers an opportunity to investigate small, medium and large residential buildings, but also other building categories such as industrial, commercial and utility buildings.

Application of results

The city has not updated its urban plan since 1994 with the new urban plan being due to 2022 (*Připravovaný územní Plán Města Brna*, 2022) and insights from the study could be potentially used for the implementation of the new urban plan. In the greater context of the circular economy and Green Deal, which prescribes EU members to decrease their reduction of net greenhouse gas emissions by at least 55% by 2030 and net zero by 2050 (World Economic Forum, 2021), prospecting and exploration of the urban mine in the Czech Republic could contribute to the roadmap for the intended reductions. In terms of circularity in the building sector, the Czech Republic achieved a 6.9%-7.6% of circular material use rate between the years 2014-2016, while the European average is 11.7% (*MPO,* 2019a). At the same time, the construction and demolition materials in the Czech Republic represent 58-65% of waste materials during 2010-2017 (*MPO,* 2019b). The ambition of the Ministry of Industry of the Czech Republic is to improve circular material use in the building sector.

1.4.1 Location characteristics

Brno is the second largest city in the Czech Republic, located in the South-Moravia Region on the confluence of the rivers Svratka and Svitava in the south-east region of Czech Republic called Moravia, as can be seen in figure 1.2. Historical archives date the first settlement in this area to the period around the year 1091 (Čapka, 2003).

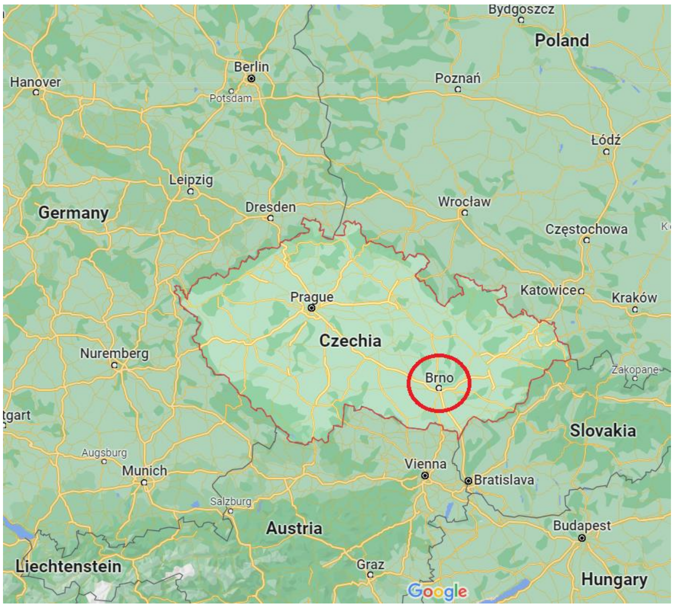


Figure 1.2 Location of Brno in Czech Republic (Google Maps, 2022)

The total area of the statutory city is 230 km^2 and about 3.170 km^2 including the metropolitan area, as can be seen in figure 1.3. The statutory city consists of 29 districts, as can be seen in figure 1.4 with a population of around 380.000, and almost 700.000 inhabitants including the metropolitan area (Ouředníček et al., 2020). In this study, these 29 districts will be taken into consideration. The reason for this is that these 29 districts constitute the Brno city and geodata are available for these districts, as further discussed in Chapter 3.

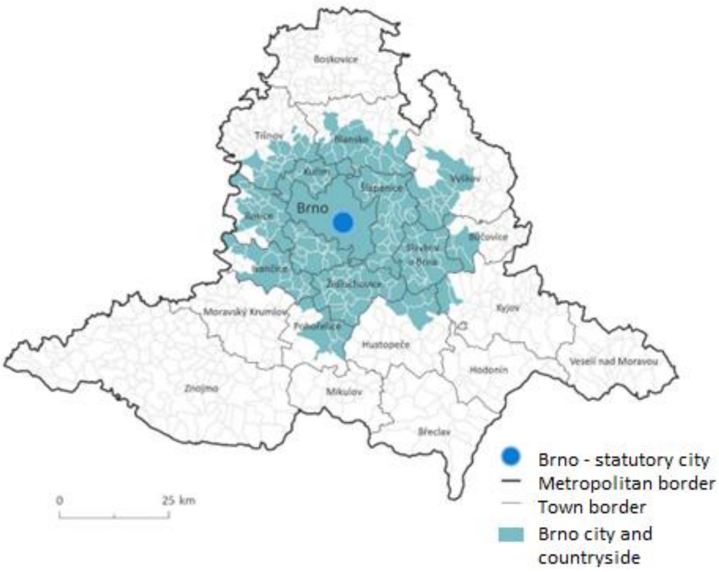


Figure 1.3 Delimitation of the territory of the Brno Metropolitan Area (Ouředníček et al., 2020)

1.4.2 Districts and population characteristics

Figure 1.4 shows all the 29 city districts that belong to the statutory city delineation of Brno. The historical city centre located in the Brno-Střed district represents the most significant commercial zone; the extended historical city centre spans within the same district across cadastral areas Staré Brno, Trnitá, Zábrdovice, Černá Pole, Veveří and Královo Pole.

Brno city has numerous panel house estates originating from the communist era (1948-1989) that are located among other in cadastral areas Lesná, Vinohrady, Líšeň, Slatina, Bohunice, Starý Lískovec, Nový Lískovec, Bohunice, Kohoutovice, Bystrc, Žabovřesky, Komín, Řečkovice, and one from the post-communist era, Kamenný Vrch. The most populated ones are estates in Bystrc, Líšeň, Bohunice, Vinohrady, Starý Lískovec, Lesná and Kohoutovice each housing more than 10.000 residents (Sčítání lidu - Census, 2011). The recently developed extensions of the city build-up (since 1998) are located in cadastral areas Černovice, Slatina, Horní and Dolní Heršpice, Bohunice, Žebětín, Bystrc, Královo Pole, Medlánky, and Ivanovice. Modern high-rise buildings can be found mainly in areas Královo Pole, Starý Lískovec, Bohunice, which are major technology and education hotspots, and Brno-Jih, with a large commercial and administrative zone. Brno-Jih, along with areas Černovice, Slatina, and Tuřany, represent large industrial and warehousing areas. Additionally, Brno-Jih, Zábrdovice and Černovice are also characterized by numberous brownfields, which are run-down industrial areas that are currently demolished or reconstructed for future purpuses (data.brno, 2021a).

Two hills located around the city centre dominate the panorama of the city, with landmarks such as the Špilberk castle from the 13th century and Petrov Cathedral, each located on one of these hills. The Špilberk castle is surrounded by a hill park, and the largest park, Lužánky, is located in Černá pole. Another significant building is the UNESCO protected Villa Tugendhat, which is a significant building for modern architecture in Europe located in Černá Pole. Masaryk Circuit located in Žebětín is a motorsport race track, which hosted Grand Prix till the year 2020. Brno has also a small domestic and international airport located in area Tuřany, and the large Brno Exhibition Centre in Pisárky.

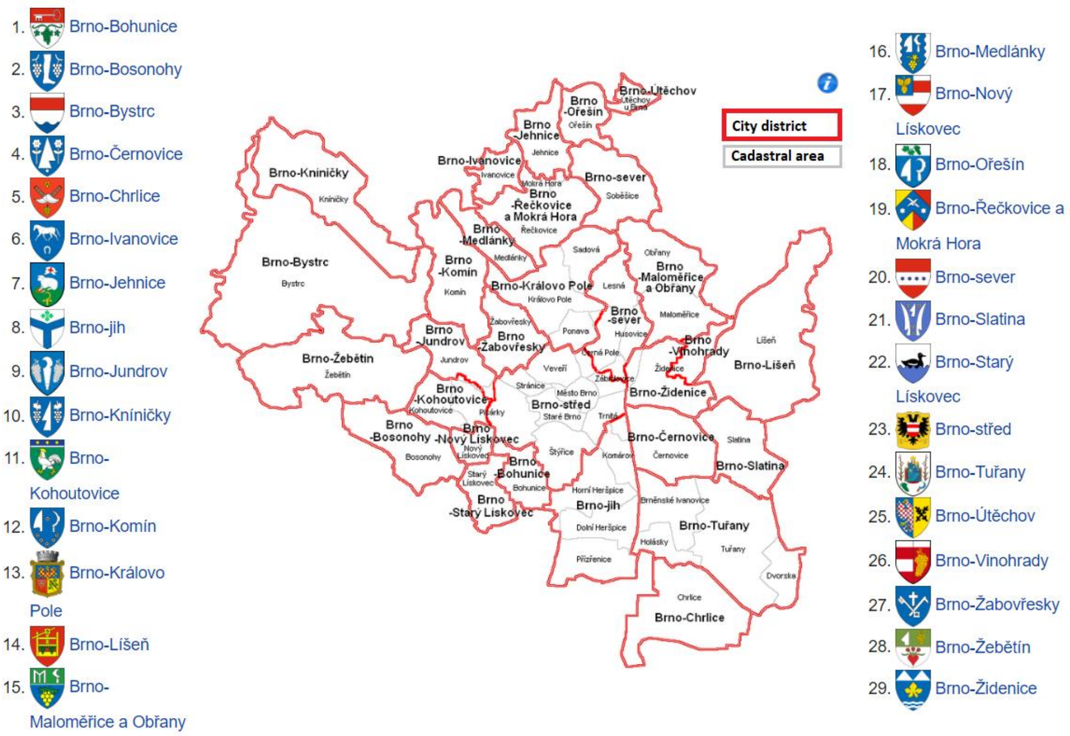


Figure 1.4 Brno - City Districts (Sčítání lidu - Census, 2011)

In table 1.1, the population, area, and population density per district are displayed.

Table 1.1 Population per district (Sčítání lidu - Census, 2011)

	City District	Population	Area [km²]	Population density [population/km²]
1	Brno-střed	64316	15	4288
2	Brno-sever	47643	12,24	3892
3	Brno-Královo Pole	28674	9,91	2893
4	Brno-Líšeň	26781	15,71	1705
5	Brno-Bystrc	24218	27,24	889
6	Brno-Židenice	22000	3,03	7261
7	Brno-Žabovřesky	21047	4,35	4838
8	Brno-Řečkovice a Mokrá Hora	15486	7,57	2046
9	Brno-Bohunice	14683	3,02	4862
10	Brno-Vinohrady	13361	2,28	5860
11	Brno-Starý Lískovec	12931	3,28	3942
12	Brno-Kohoutovice	12621	4,09	3086
13	Brno-Nový Lískovec	11349	1,66	6837
14	Brno-jih	9690	12,77	759
15	Brno-Slatina	9360	5,83	1605
16	Brno-Černovice	8024	6,29	1276
17	Brno-Komín	7457	7,6	981
18	Brno-Medlánky	5898	3,51	1680
19	Brno-Tuřany	5674	17,84	318
20	Brno-Maloměřice a Obřany	5621	9,36	601
21	Brno-Jundrov	4132	4,15	996
22	Brno-Chrlice	3722	9,5	392
23	Brno-Žebětín	3577	13,6	263
24	Brno-Bosonohy	2457	7,15	344
25	Brno-Ivanovice	1746	2,45	713
26	Brno-Jehnice	1102	4,07	271
27	Brno-Kníničky	1006	10,92	92
28	Brno-Útěchov	760	1,18	644
29	Brno-Ořešín	577	3,07	188
	Total	**385 913**	**228,68**	**1688**

1.5 Research aim

The research aim is to determine the current material stock in buildings of the 29 districts in the statutory city of Brno, Czech Republic. The first objective of the research is to create an inventory of the current material stocks in buildings and draw insights based on the results. The second objective is to put the results in the context of circular economy of the C&D industry in Brno and Czech Republic to devise recommendations for the future policy-making efforts. Hence, the research aim is two-fold – analysing data to **obtain results and insights using GIS tools** and contextualization for **policy relevance** so that insights can be translated into recommendations. The GIS analysis plays larger role in this study, while the policy relevance aspect of this study is limited to gaining understanding of circularity of C&D industry rather than in-depth analysis of the policy area of C&D circularity.

The research sets out to contribute to the understanding and improvement of circularity, and more specifically urban mining in the building sector, by creating an inventory of material stock and providing insights into how the results can be translated into actionable recommendations.

1.5.1 Research scope

As for the scope of the geographical analysis, it concerns the 29 districts of the statutory city Brno and pertains only to buildings, i.e. excludes other structures, infrastructure, or underground installation. Three structural materials were selected - concrete, bricks and mortar - and only buildings with residential and non-residential functions are considered. In regard to the construction year of the buildings, all periods are included in this study. The temporal scope of the geographical analysis is limited to the current stock of building (up to 2020), therefore, only a snapshot of buildings material stock that was present in Brno at that time is provided. The scope is further discussed in the Methods and Data section, where the specific categorization and selection is elaborated and justified.

As for the scope of the result contextualization for policy recommendations, a broader perspective is taken to link the research to the multidisciplinary and systematic approach of the industrial ecology discipline. This means looking at different levels of this highly complex matter – building level, local and national/European level – as well as translating and contextualizing results and insights from the GIS analysis into recommendations. In the context of this study, it is understanding the existing frameworks, concepts, challenges, and trends, so that the GIS results can contribute to the broader picture of circularity in the C&D industry. The relevant information for this part are researched and presented in Chapter 2, and later used in Chapter 5 and 6 to provide recommendations.

1.5.2 Research questions

Based on the problem description, research gap and review of other case studies, the following main research question was chosen:

> *What is the current building material stock in the urban mine of Brno, Czech Republic, and how can this knowledge be used to improve the building sector circularity?*

Sub-questions
Based on the proposed methods, the following sub-questions have been devised:

1. What geographical data and attributes are available for buildings in Brno?
2. What approach has to be taken based on the existing data in order to generate the material stock of concrete, bricks and mortar of buildings in Brno?
3. What is the spatial distribution and total material stock in buildings in Brno?
4. How can the material stock of buildings in Brno be characterized and interpreted based on the results?
5. How can the findings be translated into actionable recommendations for relevant stakeholders for improving the circularity of the C&D sector?

1.5.3 Approach
The research involves a level of interdisciplinarity as shown in the research gap and research aim section above, meaning that it is not solely pertinent to analysing material quantities, but requires use of outputs from other disciplines and places results of the analysis into socio-technical context.

When studying circularity of materials, the disciplines of material engineering and civil engineering are relevant for determining material intensities for different types of building functions and years these buildings were constructed. However, does not delve into these disciplines, and only uses the results of these disciplines. This study concerns actors such as universities, governmental institutions (e.g. ministries, municipality), construction and demolition companies, and other agencies (e.g. architectural office, research institutes). These actors are both the ones who might be in possession of the necessary data but are also the factual end-users of the study's results.

The research utilizes the geographic approach, which is an approach widely used in other spatial studies (Artz & Baumann, 2009). Geographical information systems (GIS) are used in many disciplines (*What Is GIS?*, 2022) and in this research, it represents the main tool to manage geodata, calculate the material stocks, visualize, and interpret the results. In the policy relevance part of this study, the results are analysed to create policy recommendation that can be applied to the specific geographical, economic and political context of the case study. Such analysis concerns review of documents, frameworks, and guidelines devised by European, governmental, municipal and other relevant bodies that participate in decision making. Therefore, the interdisciplinarity of this research spans from understanding material stocks on the level of individual materials and buildings, on the level of the whole city and related total material stocks, and on the governance level.

1.5.4 Relevance to Industrial Ecology
As discussed in the research gap section, Industrial Ecology attempts to further the research on secondary material use and urban mining on the material stock level of socio-technical systems. The case study of this research contributes to this by estimating the material stock of selected construction materials in buildings for a selected city. The value of this research for the scientific community lies in creation of a material stock account for a city and region that has not been researched yet, and therefore expands the research and allows for comparison with other studies. It also evaluates and applies concepts and tools from transition and governance to yield relevant policy recommendations. Therefore, it produces examples for the field of Industrial Ecology how quantitative results from geographical approach can be contextualized in the political and economic context, such as circular economy and the Green Deal.

1.5.5 Thesis outline

To conclude this chapter, this thesis sets to investigate the material stock of concrete, bricks, and mortar of the current stock of buildings in the 29 districts of the Statutory City of Brno, Czech Republic. It uses the GIS bottom-up analysis as the main method to arrive at total material stock of these materials, utilizing tools and functions of the ArcGIS software based on geographical data, namely building objects, surface area, number of floors, building function, construction period, and material intensities. Attention is given also to understanding the circular construction and demolition industry as to what its characteristics are, actors, challenges, barriers, tools used for improvement of the circularity, areas of interest and insights into the context of circular C&D in Czech Republic. By combining these two elements, of which the GIS analysis plays a major role, the GIS analysis results are placed in the context of policy relevance for the circular C&D in a form of recommendations for relevant actors. The goal is to answer the main research question: '*What is the current building material stock in the urban mine of Brno, Czech Republic, and how can this knowledge be used to improve the building sector circularity?'* Answering this question by conducting such case study adds to the current research into secondary material use with the focus on the discipline of urban mining.

2. Chapter: Background information

In this chapter, the existing literature and other sources are reviewed to gain understanding of the concepts relevant to this study and to select an appropriate approach for this research project.

The chapter is divided into two main sections that relate to the two aims of this study. The first section focuses on the geographical aspect of this research, which includes concepts from the geographical approach, research methods and GIS tools. The second section focuses the policy aspect of this research covering frameworks, concepts, actors, challenges, and trends from the C&D industry in relation to circular economy. This chapter therefore serves to devise the right methods for studying the material stocks for the geographical analysis and gaining insights into the circular C&D in order to navigate the application of the GIS analysis results.

2.1 Geographical analysis

The geographical analysis is a direct response to the problem and research gap described in the Introduction chapter and its goal is to zoom in on a specific, researchable, and quantifiable issue. This section is structured in a funnel-like fashion, where first the general concepts pertinent to sustainability of the construction industry are discussed and then the approach for studying the matter is presented. Next, the method for conducting such research from the existing literature is reviewed, followed up by discussion on the use of specific tools and data requirements. This section therefore clarifies relevant concepts and topics and presents approaches used in the existing literature, in order to inform the next chapter for a choice of specific method and data suitable for this research.

2.1.1 Built environment stock research

The research into the built environment stock, i.e., material stock in buildings and infrastructure, has been reviewed by Lanau et al. (2019), where the authors reviewed the progress and prospects of this discipline. They summarize that the up-to-date research studies material stock from the perspective of different categories (mobile, non-mobile stock), typology (in-use, end-use), and materials (metallic, non-metallic); using varying units of measurement (items, length, weight, area, volume) and display indicators for comparability (relative to land area, population). The studies also differ in geographical scales and resolution (neighbourhood, urban, regional, national, multinational, global, temporal scope (static, dynamic), and applied approach (top-down, bottom-up, remote sensing). The research into material stock is also motivated by distinct purpose (identification of trends, patterns, and drivers; scenario development; material accounts; and spatial distribution), which renders implications for diverse stakeholders.

The above aspects of material stock research represent the variables that need to be considered in a study. The aspects of category, typology, material, and geographical scale have been determined in the previous chapter. The aspects of approach and purpose are discussed in this chapter, while the aspects of measurement, indicator for comparability and temporal scope are addressed in Chapter 3.

2.1.2 Circular economy

A concept of circular economy has been gradually adopted by the EU, many national governments, and companies. It proposes a transition from a linear system, where products are extracted, produced, and disposed of, to a closed-loop system, where outputs of one process are inputs of another process and no waste is created (Korhonen et al., 2018). The circular economy was formally defined as ''*an industrial system that is restorative or regenerative by intention and design. It replaces the end-of-life concept with restoration, shifts toward the use of renewable energy, eliminates the use of toxic chemicals impairing reuse, and aims at eliminating waste through the superior design of materials, products, systems, and business models*'' (Ellen MacArthur Foundation, 2015). Different strategies and concepts exist that can be applied to 'close the loop', for instance the self-explanatory 'reuse, reduce or recycle' of materials, products, and their use. In terms of material stocks of the built environment, it concerns moving away from dependency on primary resources (virgin materials) to fulfil our societal needs and focusing on the recovery of secondary materials (recycled materials) from the existing material stocks. These stocks are referred to as **anthropogenic**, or technospheric stocks, which carry great potential as a source of materials (Johansson et al., 2013). Extraction of these secondary materials, which are often found in large quantities in industrialized societies, is referred to as **urban mining**, as opposed to mining of primary resources found in natural mines (Cossu & Williams, 2015).

2.1.3 Urban mining

The urban mining process is similar to the process of natural resource mining and hence is also based on that process. Lederer et al. (2014) propose a framework for anthropogenic stock evaluation as a 4-step process – prospection, exploration, evaluation, and classification, as can be seen in figure 2.1 below.

Evaluation step	Method	Result
1. Prospection	Identification of stocks based on macro-level MFA	Relevant anthropogenic stocks identified and estimated
2. Exploration	Detailed stock characterization based on micro-level studies	Grade, size of stock, uncertainties
3. Evaluation	Selection of technologies and economic analysis of costs and revenues	Costs/revenues ratio
4. Classification	McKelvey cross classification	Reserves, resources, and other occurences of anthropogenic stocks

Figure 2.1: Anthropogenic stock resource evaluation (Lederer et al., 2014)

The **prospecting** step is done with the use of a tool called material flow analysis (MFA), which purpose is to quantify the flows and use of materials in a top-down manner, meaning the net additions to stock are used to come up with a total stock size (Behrens et al., 2007). Another way to do prospecting is through input-output analysis, which uses economic data to determine the stock size (Lederer et al., 2016). This step identifies materials and generates estimates of the material quantities, but alone does not provide sufficient details about the stock characteristics. The next step, **exploration**, provides higher resolution information on a micro level, such as stock size, occurrence, grade, and uncertainties, which are more actionable for the actual mining processes and policymaking (Lederer et al., 2014). Step 3, **evaluation**, serves for determining the technology to be used for the extraction and associated costs, while step 4, **classification**, evaluates the economic feasibility of secondary material extraction and production of marketable products these resources (Lederer et al., 2014). Steps 1 and namely step 2 are mostly relevant for this study, therefore, steps 3 and 4 are not further discussed.

Looking into examples of research in the context of this study – in-use stock of construction materials in the building sector – research related to the prospecting level has been conducted on a national level and on a per capita level, to estimate the quantities of resources that are currently present in the society, for instance by Fishman et al. (2014). Other research studied material stocks per economic sector and product category, which pointed to the building sector as the one that contains the largest material stocks (Lederer et al., 2014). While these investigations give the idea of the material stock magnitudes per sector/product characteristic for the prospection step of urban mining, more detailed information, which can be obtained through the exploration step, is necessary to create practical and actionable insights on specific materials of material stock to motivate meaningful policies (Lederer et al., 2016).

2.1.4 Top-down and bottom-up approach

Currently, cases that assess the stocks can be generally divided into two complementary approaches – top-down and bottom-up (Augiseau & Barles, 2017). The top-down approach, generally used in the first evaluation step of urban mining, arrives at material mass (material stock) mainly through aggregated economic data such as environmental accounts, trade data, and waste statistics in metric, monetary and mass terms. This approach provides a complete picture; however, it is only pertinent to material flows and does not provide high resolution of results, therefore, it is suitable for the prospection step. The bottom-up approach arrives at the material mass of both stocks and flows based on granular stock and flows data, such building objects, by counting objects one-by-one. It provides higher resolution because it differentiates functional units such as building area, function, number of floors, building age, and material compositions. The downside of the method is that material mass results are incomplete and prone to inaccuracy (Schiller et al., 2017). The bottom-up approach is suitable for the exploration step of the stock evaluation.

These two approaches are summarized in figure 2.2 below.

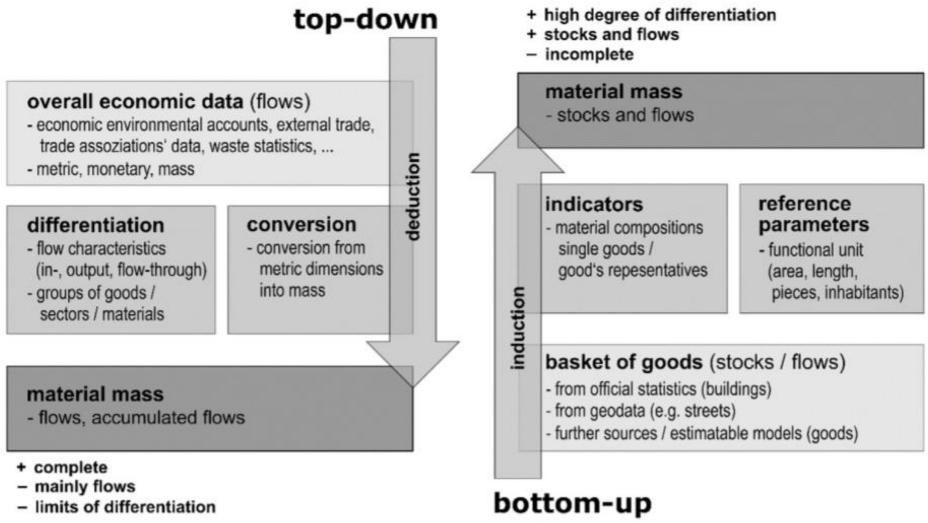


Figure 2.2 Top-down vs. bottom-up approach (Schiller et al., 2017)

Aside from the bottom-up being useful for providing an understanding of the infrastructure features (Lichtensteiger & Baccini, 2008) it also offers relevant insights into the spatial and temporal dynamics of the stocks and flows (Heeren & Hellweg, 2019). Due to this, many studies focusing on understanding the stocks and flows with the bottom-up approach utilize geographic information system (GIS) modelling, especially in the built environment concerning buildings and infrastructures (Augiseau & Kim, 2021) as is demonstrated in the next paragraph.

The GIS software enables digitization of objects and assigning them attributes (e.g. number of floors, building function, address, year of construction, etc.) including geo-location (Sumathi et al., 2008). These objects are presented in layers that can be stacked on top of each other, and contain objects (from trees, buildings to whole cities or countries), which are called features. The software displays a GIS map, which shows spatial data with an attribute table that contains non-geographic information (attributes mentioned above).

2.1.5 Bottom-up approach in case studies

In order to gain a basic understanding of what was done in other studies and what results they yielded, a literature review is carried out for different case studies that used the bottom-up approach studying the building sector.

In a study on Padua, Italy, Miatto et al. (2019) estimated material stocks, lifespans of buildings and future flows of construction materials such as mortar, concrete, steel, bricks, timber, glass, insulation and other materials from the residential and non-residential building. Kleemann et al. (2017) estimate material stocks of bricks, mortar, concrete, wood, steel and other materials in Vienna. Schandl et al. (2020), delivered a study on concrete, sand and stone, steel, ceramics and other materials in the Canberra suburb of Braddon in Australia. A comparable study was done by Cheng et al. (2018) in Taipei, Taiwan. Lanau and Liu (2020) conducted a study on buildings, roads, and pipe networks in Odense, Denmark. Augiseau and Kim (2021), carried out a study on 27 materials and 24 building archetypes in the Paris region. This is just a short list of studies using the bottom-up GIS approach which gained popularity about 20 years ago. They share the utilized approach with a focus on the geospatial and temporal dimension, where the results are spatially distributed and accounted for over a period of time, mostly during the period of the last 100 years. Generally, they provide insights into built environment material content, location, and age (Augiseau & Barles, 2017). These studies help understand urban metabolism, which is the process of resources being transformed by labour and capital to fulfil the needs of the society (Fischer-Kowalski & Hüttler, 1998). They can assist with future waste management, policy-making or urban planning (Schandl et al., 2020).

Based on these studies, room for future research and research gap can be articulated. Augiseau and Barles (2017) suggest future research that further investigates the problematic assumptions and data related mainly to the lifespans of material stocks and the material intensities used for calculating the stocks. They also propose to couple the bottom-up and top-down approaches to increase the reliability of the material estimations. Kleemann et al. (2017) address building structure data, especially in regard to the size of the building and their mapping in GIS, so that more accurate sizes and shapes of specific building features can be used for calculations of the results. Additionally, Kleemann et al. (2016) call for more available open-source data and more specific data on material intensities for different building categories. Furthermore, case studies need to be conducted at the locations, where governments or municipalities want to implement urban mining. For the sake of research, the more case studies are carried out the more material inventories across different regions are available to provide comparisons between regions with different economic, geographical, or developmental features. To demonstrate this, Miatto et al. (2019) pointed out that material stock per capita in Japan is about 2.5 times higher than in Europe because buildings in Japan have to take into account frequent earthquakes. More case studies would provide better insights into the level of service that material stocks provide in different regions or in comparison between urbanized areas or rural areas. Furthermore, it should be noted that most studies using the bottom-up GIS approach were conducted on cities in countries in Western Europe, the US, Australia, and countries of East Asia, such as China, Japan and Taiwan (Lanau et al., 2019).

2.1.6 Application of GIS results

In this section, it is discussed how the results of GIS analysis are used in practice to motivate actionable recommendations in the context of urban mining and circularity of the construction and demolition industry.

Paz et al. (2018) explain that GIS is mainly used for "the *spatial analysis of CDW from generation, sorting, collection, transportation to disposal destinations*". At a regional level, GIS applications allows for predictive and comprehensive overview for C&D material flows. In combination with other technologies, it can enunciate the different material flow, territories and groups of actors and their interrelations, as well as facilitating translation of complex information of material flows into actionable and practical knowledge for actors in the urban planning process (Arciniegas et al., 2019). Therefore, the applications of GIS in the C&D industry provide many opportunities to retain material value and underpin the CE transition.

The GIS capacities were used to support decision-making on the characterization, collection and sizing optimization of landfill in relation to municipal waste management (Lella et al., 2017). GIS was introduced by other studies into the building sector for the management of construction resources and C&D waste. It was used by Wu et al. (2016) in Shenzen for mapping and characterization of the C&D waste generation and flows in order to develop a new management approach for C&D waste. In another case study in Shenzen, Wang et al. (2019) used 4D-GIS model (including several time series) for prediction and determination of volumes and positioning of new landfills, and for construction material and C&D waste tracking. It was postulated that this could be also used to improve the C&D waste management system and building material reuse in order to reduce the environmental impacts of urban renewal.

2.1.7 Geographical approach

Conducting research with GIS implies a study with a spatial component, and for this study, the geographic approach for spatial studies is selected. This approach consists of 5 steps (Artz & Baumann, 2009):

1. Ask – answering fundamental questions about the research, such problem definition, location, stakeholders, description of the ideal final outcome, and form of presentation
2. Acquire – defining which data and formats are needed and how can they be acquired
3. Examine – deciding how will data be stored and what conversions are necessary
4. Analyse – deciding what (spatial) analyses are necessary and in what sequence
5. Act – producing and interpreting results and translating them into actionable items

The geographical approach is used as a research framework and its application in this study is elaborated in the Methods and Data section.

2.2 Policy and Actor aspects

Section 2.2 reviews existing literature and other sources to understand the broader perspective of the circularity in the C&D industry, to which the results of GIS analysis can be later placed.

This review focuses first on understanding general frameworks and concepts of circularity in the C&D industry, as well as challenges, trends and strategies. This way, specific areas can be identified, where the results of the geographical analysis can be utilized and leveraged to inform more sustainable practices in the industry. The review intends to understand the issues on both strategic level and specific level, identifying existing frameworks, relevant stakeholders, challenges, application of tools and specific areas of interest in the context of GIS analysis. Finally, review also looks into the context of C&D industry in Czech Republic, recognizing frameworks, characteristics and current status of C&D relevant to the location of this study.

Therefore, this part of the literature review aims to understand and later address the specific context, in which the results of the GIS analysis, instead of providing an extensive and exhaustive overview of literature on the topic of circular C&D.

2.2.1 Circularity in construction and demolition industry

The concept of circular construction and demolition is diametrically different from the current, mostly linear practice of the construction and demolition. Ellen MacArthur Foundation defines circular economy for built environment as ‘‘restorative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles‘‘ (2015). Construction and demolition is a complex process with many distinct activities, inputs and stakeholders resulting in complex products, which are buildings. Circular buildings are defined by Pomponi and Moncaster as ‘‘buildings that are designed, planned, built, operated, maintained, and deconstructed in a manner consistent with circular economy principles‘‘ (2017). In order to achieve circularity in the C&D industry, not only the building must be circular but also all the actors along the whole supply chain must collaborate and act in ways that promote a foster circularity across all of the stages along the whole supply chain.

2.2.2 Actors in the (circular) C&D arena

Before moving to specific issues of the circular C&D, it is useful to briefly map the relevant stakeholders involved in the circular C&D industry. Using a snowball method, 5 different sources were reviewed to identify the individual stakeholders and group them in 20 categories below. The reviewed sources are listed below, and their numbers are used to reference the occurrence of each role in the reviewed source:

1) (Ghaffar et al., 2020)
2) (Shooshtarian et al., 2022)
3) (Mahpour, 2018)
4) (Hossain et al., 2020)
5) (European Commission, 2020)

Table 2.1 below shows the identified groups of stakeholders along with a short description of their role in the circular C&D.

Table 2.1 Actors in the circular C&D arena

	Actor	Responsibility/task	Sources
1	Investors, property developers	Sponsors and essentially the clients of the construction process	5
2	Designers, architects, civil engineers	Professionals responsible for technical and aesthetical design of the buildings	4, 5
3	Project management	Team behind coordination of all involved parties	3
4	Material manufactures and suppliers	Extraction/buying and processing of raw materials (e.g. sand, clay, glass) for manufacturers of construction products	3, 4
5	Manufacturers and suppliers of construction products	Production of construction products (e.g. concrete, bricks, windows)	3, 4, 5
6	Manufacturers and suppliers of machinery	Production of machinery and tools used for construction, demolition, and waste processing (e.g. bulldozers, cement mixers, scales, sorting machines, crushers, etc.)	2, 3, 4
7	Constructors, contractors and builders	Construction of the building and different installations (e.g. structures, water piping, electricity, sanitation, etc.)	1, 2, 4, 5
8	Building users	Those who use the building (e.g. tenants, companies, etc.)	5
9	Facility managers and owners	Those who oversee, manage, and maintain the objects	5
10	Demolition and deconstruction companies	Companies in charge of decommission and disassembly of the object	1, 2, 5
11	C&D waste management, recovery, delivery and transport, waste processing companies, recyclers	Companies in charge of administration, sorting, pre-processing, assignment and transportation of waste materials and products, including companies that process and remanufacture waste into secondary resources, and energy recovery from waste (e.g. incinerators)	1, 2, 3, 4
12	Landfill	Waste disposal and storage of unused waste at the end-of-life	2
13	Government, legislators, regulators, local authorities	Institutions in charge of setting up guidelines, legislatorial frameworks, laws, regulations, taxes, and rules for the C&D industry	2, 3, 4, 5
14	Environmental protection and enforcement	Authorities that guide, monitor, inspect, penalize and generally enforce the established regulations	2, 3
15	Industry association	Organized bodies from the industry that defend the interest of the given group (e.g. construction association)	2
16	Insurance providers	Provide insurance for machinery, materials, and whole objects	5
17	R&D, research institutes, universities	Institutions and organizations that generate new knowledge	2, 4
18	Consultancy and institutes	Companies that deliver industry-specific knowledge (e.g. training, education, expertise)	2
19	Human sciences	Mentioned separately from 16), as they generate new knowledge and insights for social and governance aspects of C&D	3
20	Public	General public that can voice their opinion, organize, protest or support ideas	4

2.2.3 General challenges for transition towards circular C&D

This section focuses on identification of specific and tangible issues of C&D circularity, therefore this section focuses on relevant aspects of circular C&D. Hossain et al (2020) conducted an extensive review of literature in search for trends, challenges and possible solutions, and they identified 10 key areas of interest in the C&D circularity, which are discussed below:

- Design
- Material selection
- Supply chain
- Business model
- Relevant policy
- Uncertainty and risk
- Collaboration among actors
- Knowledge among stakeholders
- Integration of urban metabolism
- Methodology for CE evaluation

Design relates to the adoption of CE principles in terms of materials and components in relationship to the end-of-life already during the process of designing. The existing barriers mainly pertain to issue of ownership during the end-of-life phase, poor sustainable waste management integration and uncertainty of waste management of C&D materials.

Material selection in relevant for the choice of more renewable materials with highlighted issues related to tracking of recycled materials, recycled products quality, and uncertainty when it comes to reuse or recycling of these materials due to safety and performance.

Supply chain of C&D consists of many actors that are required to cooperate in order to achieve higher levels of C&D circularity. It has been recognized step towards circularity is hindered by a lack of incentives for involved parties, risks related to inconsistent supply, uncertainties, lack of mutual interest and mismatch in perceptions across the supply chain.

Business model represents an issue despite many existing CE frameworks due to a lack of a fitting circular building business model. Existing models that do not represent a good fit face challenges in terms of life cycle costs, need for innovative business models, standardization of refurbished products, prices of recycled materials, insufficient incentivization for reuse and recycling of materials, and ownership issues such as lacking take-back systems by producers.

Relevant policy is highlighted by the existence of resource policies focused on the efficient use of resources in place of material demand reduction in the first place. It is mentioned that setting requirements and criteria in public procurement can support extending product life span and efficient use of secondary materials. Regulations and policies by local and national authorities are to play an important role in encouraging and enforcing CE.

Uncertainty and risk relate, among economic, supply and business risks, to missing guidelines and tools for circular design of both materials and buildings, and mainly to uncertainty about the reuse of materials after the end-of-life phase.

Collaboration among actors is deemed vital for a collaborative process across the whole supply chain that would adhere to the principles of CE. Most often challenges faced in such process are poor communication among designers, contractors and clients, insufficient acceptance of the idea and principles of CE, and leadership.

Knowledge among stakeholders on the social and institutional level about CE is important for understanding the implications for their role in the projects. Raising awareness, education and vision-making with the use of education and training is necessary to adjust the practices of both citizens but also constructors in relation to recycled and reused products.

Integration of urban metabolism or industrial symbiosis, as a subset of CE, can be used to use one's waste as a resource for another party or improve the efficiency of resource use in order to close the loop. It requires the identification of drivers for resource flows, material flow trends, and CE implementation evaluation.

Methodology for CE evaluation means a complete CE assessment of a building, including implementation guidelines and indicators. Problems arise due the complexity across the supply chain, where each process such as design, material selection, end-of-life have different perspectives and considerations that are not harmonized for a holistic CE approach.

2.2.4 Tools for C&D circularity improvement

In their study, Yu et al (2022) discuss the use of different decision support tools based on information & communication technologies in relation to circular economy in the construction industry. This study reviewed a large body of research to determine, which tools and technologies (such as Building information modelling, GIS, Radio frequency identification, Big Data Analysis, Modelling & Simulation) are mentioned in literature in relation to:

- Usefulness for circularity principles (reuse, reduce, recycle)
- Aspects they contribute to (environmental, economic and social sustainability)
- Who are their target users (designer, construction manager, material supplier, demolition manager, governmental body, or not specified)
- And its level of comprehensiveness (conceptual, experimental, comprehensive, or not specified)

Since the research project of this thesis focuses on analysis with GIS, only aspects relevant for GIS are discussed. GIS is considered:

- Useful purely for the reuse and recycle circularity principles
- Mostly relevant for the environmental aspect of sustainability, and only fractionally for economic and social aspects
- The most relevant target user is the government, partially useful for the demolition manager, and fractionally for construction manager and material supplier
- To be useful mainly in experimental studies, followed by partial use in conceptual, and miniscule use in comprehensive studies

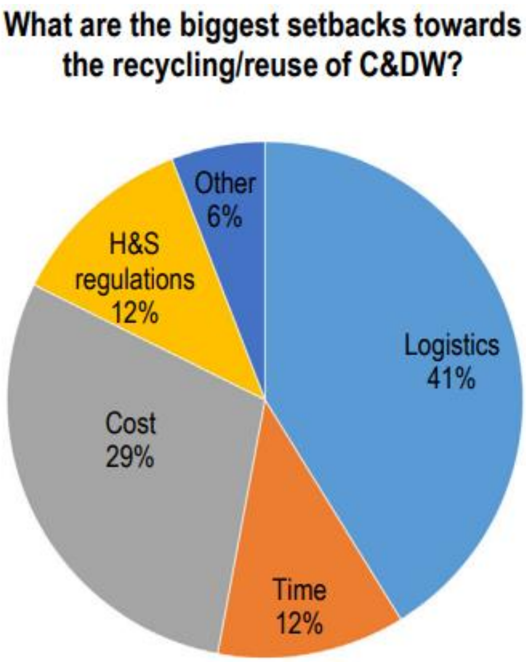
The key take-aways for this thesis research are that focus of the results contextualization should lay in the reuse and reduce principles, with recommendations tailored to government and demolition companies. Since the focus of the GIS analysis is already selected, the other two insights are not further relevant.

2.2.5 Reuse and recycle in C&D

Since reuse and reduce principles were recognized as the most relevant for application of GIS, further review is conducted to understand these principles. Blengini and Garbarino (2010) characterize these in a way that "*Re-use typically requires minimal processing before reapplication in a similar context, whereas recycling is breaking down waste into a homogeneous material for a lesser value application or introduction as replacement feedstock for remanufacturing of components*". This section reviews number of articles about reuse and recycle in the C&D industry in a snowball manner to identify the common challenges.

Ghaffar et al. (2020) state the there is a lack of knowledge and experience when it comes to the reuse of the construction products. Additionally, this practice is also met with hesitance due to safety, performance, and price of quality assurance issues. Recycling faces challenges related to both technical and economic aspects. There are existing technological limitation and hurdles for recycling, which are in some cases unavoidable (e.g. toxic materials), but for some of the materials, recycling technologies that are present in other countries, are simply missing. As for the economic aspects, the product must demonstrate competitiveness in terms of costs (cheaper than products made of virgin materials), quality (perform same as products from virgin materials or be used in an object with for instance shorter life span or less requirements), and quantity (must be readily available). This is often not the case due to missing standardization, lack of supply of these materials, small number of companies that carry out necessary waste processing and remanufacturing processes, and finally slow growth of these companies (Yuan, 2017).

Research conducted by Huang et al. (2018) into the C&D waste management in China confirms and points out other issues. These are for instance low costs for waste disposal, which do not incentivize the economic efforts required by reuse and recycling. Secondly, poor guidance and regulation in terms of collection and sorting of C&D waste cause waste materials to be either polluted with other materials or incorrectly sorted, which results in low reuse and recycling efficiencies. Shooshtarian et al. (2022) add that these waste-related regulations and plans must be effectively encouraged and implemented in order to be implemented, and they highlight the role of R&D that is vital to support this. Next mentioned by Huang et al. (2017) are insufficient communication, collaboration, and a missing system for sharing information among the different agencies responsible for waste management (e.g. different levels, transportation, supervision, inspection, etc.). To this issue, Yuan (2017) also adds that not only the involvement of different agencies and their communication is a problem, but that one leading agency or department should be the end-accountable for a complete and seamless C&D waste management process. Shooshtarian et al. (2022) also include a notion of inconsistency in jurisdictional regulation across different region being a challenge in Australia and calls for clarification in order of the regulatory framework in order to foster the market development and implementation of effective CE. They further state geographical location and population density plays a role because long distances between demolition sites and waste processing facilities pose a barrier for market development due to transportation costs. Yuan (2017) also states that further challenges lay in insufficient attention and priritization of waste management within construction projects, and lack of essential data in the C&D waste.



For quantification purposes, Ghaffar et al. (2020) conducted interviews with industry actors (construction, demolition, and waste processing companies) within the UK's circular C&D industry, to point out, which challenges are perceived as the most severe, as shown in figure 2.3.

The logistics is perceived as the biggest bottleneck for reuse and recycling of C&D waste among these actors. This is followed by costs, health and safety regulations, time and other bottlenecks. All of the challenges discussed in the previous paragraphs can be assigned to one of these categories, this figure just gives an idea of the how are they perceived among the actors.

Figure 2.3 Bottlenecks for reuse and recycling of C&D waste (Ghaffar, 2020)

To summarize, this section discussed circularity challenges for the reuse and recycling principles of C&D waste from various studies across the world and other extensive reviews. These can be shortly summarized in the following list:

- Lack of knowledge and experience with reuse products
- Technical limitations in recycling
- Competetivenes in terms of costs, quality and quantity
    - Costs – lack of economic incentives (low taxes and costs for waste disposal)
    - Quality – Lack of standardization of secondary materials and regulatory hurdles
    - Quantity – Underdeveloped market in terms of supply of materials and waste processing companies
- Regulation and guidance for collection and sorting of C&D waste and its jurisdictional inconsistency
- Awareness, attention, prioritization, encouragement and enforcement of regulations and circular practices underpinned by R&D
- Communication and collaboration among various regulatory and eforcement institutions
- Leadership role of one agency
- Geographical location, population density and transportation costs
- Lack of data in C&D waste

2.2.6 C&D circularity in Czech Republic

In this section, relevant frameworks and trends in C&D circularity in Czech Republic are discussed as well as other European frameworks and their relevancy for this research.

Strategic framework for circular economy of Czech Republic 2040

As part of the Environmental Implementation Review 2019, the European Comission requested that stated that Czech Republic needs to finalize, approve, and implement a conceptual framework for circular economy (Ministerstvo Životního Prostředí, 2022a). Circularity of the C&D sector in Czech Republic is currently spearheaded by the Strategic Framework for Circular Economy of Czech Republic 2040, in original Strategický rámec cirkulární ekonomiky České Republiky 2040, which was finalized in 2021. The strategic framework was developed between 2018-2021, was approved by the Czech Government and should be realized within the 2021-2040 time frame. The coordinator of the strategy is the Ministry of Environment, who is also responsible for implementation, along with Ministry of Industry and Trade, Ministry of Finance, Ministry of Education, Youth and Sport, Ministry of Agriculture, and Ministry of Regional Development, but there were many other institutions, industry associations, research institutions, governmental offices, regional and municipal associations involved in the preparation. The target audience of this framework are ministries, public administration, enterprises, non-profit organizations, the public, scientific and academic institutions, and schools.

The goal of the strategic framework is to provide guidance towards transition to circular economy, which aims to preserve value products, materials and resources for so long in the economic cycle as possible and return them to the production cycle at the end of their use while minimizing the creation of waste. The strategy contains an analytical and a design part. It defines a vision, global goal and strategic goals. It sets goals for individual priority areas, principles and measures for their fulfilment. The strategic framework also includes an implementation part, including monitoring.

The strategic framework addresses 10 areas of economy as follows:

1. Products and design
2. Industry, raw materials, construction and energy
3. Bioeconomy and food
4. Consumption and consumers
5. Waste management
6. Water
7. Research, development and innovation
8. Education and knowledge
9. Economic instruments
10. Circular cities and infrastructure

For this study, the most relevant area is the area 2 – Industry, raw materials, construction and energy. Per each area, firstly trends are discussed, which resonate with what has been covered in the Introduction section and the trends discussed in this literature review. This is followed by setting up of goals, principles, and measures. This document has been complemented by an Action Plan 2022-2027 that assigns each goal a guarantor, collaborators, source of financing and a deadline (Ministerstvo Životního Prostředí, 2022b). Hereby, the goals, principles and measures related to the circular C&D are shown.

Goals:

- Optimal use of materials
- Increase the use of secondary materials
- Use primary materials only when needed

Principles:

- Maximal use of secondary materials
- C&D waste is reused optimally

Measures:

- Support improvements in material flow tracking through digitization and the use of big data.
- Improve the "passportization" of new and existing buildings.
- Support practices that will lead to the development of innovative design practices for the circular economy within the construction industry.
- Explore the possibilities of applying the principles of extended producer responsibility in the field of construction.
- Support digitization in the construction industry.
- Support selective demolitions to promote appropriate management of materials from demolished buildings.
- Evaluate the possibilities of introducing requirements for the content of recycled materials for some construction products, taking into account their safety and functionality.
- Consider using the Level(s) framework to integrate life cycle assessment into public procurement.
- Evaluate legislation limiting the re-use of reconditioned and recycled material, especially road construction conditions in favour of the use of recycled aggregate.

These measures are planned to be implemented by 2040, and some of them are already addressed within the 2022-2027 time frame. Several actions are devised to implement selected measures, as shown in table 2.2 below.

Table 2.2 Action plan of the Strategic Framework for Circular Economy of Czech Republic 2040

Action	Description	Guarantor	Collaborators	Deadline
1	Evaluate the options and subsequently propose a technical standard establishing requirements for conducting pre-demolition audits for subsequent selective demolitions	Ministry of Environment	Ministry of Industry and Trade	2027
2	Promote the use of the BIM method in the private sector as well, beyond the framework of the upcoming BIM Act	Ministry of Industry and Trade	-	2025
3	Integrate the Level(S) framework into the public procurement system	Ministry of Industry and Trade	Ministry of Regional Development	2025

The goals presented in this section are discussed again in Chapter 6 – section Recommendations.

It is relevant to mention that there is a number of other frameworks, plans and agreements for circular ambitions both within the European Union and Czech Republic that this strategic plans build upon or relates to, however, it is not the goal of this thesis to cover and investigate all these documents. Therefore, the Strategic Framework was selected as the most relevant and encompassing and is discussed in the following paragraphs. Please, refer to the official document of the Strategic Framework for an overview and explanations of relations to the other frameworks.

Construction & Demolition Waste Protocol of EU

On top of this strategic plan, it is worth mentioning that the European Commission published a document called Circular Economy – Principles for Building Design, which was published in 2020 (European Commission, 2020). This document contains principles for circular C&D sector and addresses 7 target groups in the sector:

- Target group 1: Building users, facility managers and owners
- Target group 2: Design teams (engineering & architecture of buildings)
- Target group 3: Contractors and builders
- Target group 4: Manufacturers of construction products
- Target group 5: Deconstruction and demolition teams
- Target group 6: Investors, developers and insurance providers
- Target group 7: Government / Regulators / Local authorities

Since we established earlier in the literature review that the most relevant actors are the demolition companies and the government, further focus is given only to target group 5 and 7. Following are the key take-aways that are relevant for this study:

- Locations and distance between the demolition site and recycling facilities is highly important, therefore investigating these can bring additional value to improving circularity
- Identify and quantify materials contained in the buildings
- Promotion of systematic data collection in a structural way

These insights are relevant for drawing up recommendations, therefore, they are brought up again in Chapter 6. Other principles did not demonstrate immediate relation to this study. However, they might be relevant for the reader in order to gain greater understanding of the whole C&D supply chain, along with roles of the other target groups.

2.2.7 Certification, regulations, and barriers in Czech C&D circularity

In this section, the certifications, regulations and barriers in the Czech circular C&D industry are briefly discussed. It should be mentioned, that much of the information, except the ones coming from official european agencies, come from grey literature. This is due to the fact that information are simply not available, therefore, a use had to be made of various C&D interest blogs, or websites connected to consulting companies. The implications are that these information might not be reliable in the case of blogs, and in the case of relation to companies, the information might seek the interest of the company. These facts are therefore communicated and accepted, however, the information are taken at least with some level of confidence, as these are the only available sources and they at least specialize in the discussed topics.

The discourse about sustainability and circularity of C&D is mainly dominated by the topic of energy efficiency. This concerns a mandatory label that demonstrates the energy demand of the building (Zajimej.se, 2020). As for the use of certifications, circularity of buildings is declared by well-known certifications such as LEED or BREEAM, or a Czech alternative called SBToolCZ (Zajimej.se, 2020).

Such certifications are widely used for commercial buildings; however, they have not disseminated in the residential building sector. This is also due to the fact that these certifications significantly increase the construction costs and rental costs, and big companies are more likely to be able to afford it since they are also the residents, while in the residential sector, the developer tries to keep the rental costs down (Zajimej.se, 2020). Additionally, European Commission has published a free, voluntary framework for assessment and reporting on sustainability in the construction industry. This framework was created with the goal of improving energy and material efficiency in connection to the Green Deal and EU Action Plan circular economy. This framework was also formally praised by the Ministry of Industry and Trade (European Commission, 2023).

Regulations regarding recycling and reuse in the Czech Republic face currently several hurdles. Despite the existence of construction products with a share of recycled materials, standards and regulations regarding their use in construction are not clearly defined. Regulations that define the process for environment-friendly deconstruction and demolition, meaning a process where the building is taken apart rather than demolished, are also underdeveloped. Current regulation mainly address handling and disposal of toxic and harmful materials, such as asbestos (Zajimej.se, 2020).

One of the main barriers for reuse of materials is that the law stipulates that waste cannot be resold or donated; only if it is labeled as material it can become a secondary resource. All untreated by-products can be used by the same company that has produced it but it cannot be used by another party. Many actors in the C&D industry call for the development of a platform that would enable for the trading of secondary materials, which is inspired by a European project FISAAC (Fostering Industrial Symbiosis for a Sustainable Resource Intensive Industry across the extended Construction Value Chain), however, the lack of clear and effective regulations hinders development of such platform (Cirkulární Česko, 2018).

Another barrier are generally low costs of landfill depositions and also low cost for primary resources. Secondary materials provide an abundant source of materials for recycling and reuse, however, the costs of recycling, undermined by existing regulations, and lack of knowledge represent a barrier for such practices. As for the lack of knowledge, eco-innovation is a praised as one of the ways how to overcome these issues, EU promotes this for instance with their international platform Virtual Lab and the Ministry of Industry and Trade offers innovation vouchers that can be used for financing of R&D. A proper regulation and fostering of knowledge exchange is needed to shift the perception towards buildings as material banks along with material passports, which would serve as a database of materials contained in a building (Cirkulární Česko, 2018).

Looking into the most recent updates to the regulation in regarding to reuse and recycling, a stricter process for waste generation came to effect in 2022. Both construction and demolition companies must comply with the process of waste separation already at the demolition site in order to increase the reuse and recycling of the C&D waste and eliminate waste disposal, which can be fined by inspection up to 10.000.000 Czech Crowns. Another incentive is an increased fee for landfilling, which is currently at 900 Kč/ton, and will be increased to 1.500 Kč/ton in 2 years, until landfilling will be completely phased out by 2030. A key regulation called phasing out of the waste regime (in original *ukončení odpadového režimu*) will come in effect in 2025, which will stipulate criteria that, if met, will legally transform by-products and waste into products. It will also clarify and unify the conditions, under which recycled products can be labelled and sold as products, as currently, their properties are often unspecified, which discriminates these products. Under the new regulation, products that can be proven to have properties matching the harmonized standards will be able to be used almost same as primary products (Inisoft Consulting, 2022).

2.3 Conclusions chapter 2

In this chapter, the types of research, methods, and tools focused on studying the urban mine of material stocks in buildings were discussed for the research design and methodology to be drawn up. The geographical approach is used as the research framework, which will use the GIS bottom-up approach as its method. Additionally, general overview in the field of circular C&D were described as to understand where gains can be made with the use of a GIS analysis. Particularly, it was recognized that GIS analysis can benefit the improvement of the reuse and recycle strategies for improvement of circular C&D, which is mostly relevant to the government, local authorities, and demolition companies. Therefore, the research in the next chapter is designed to produce results for material stocks of buildings that can be later interpreted and translated into recommendations for the actors mentioned above in order to improve the reuse and recycling of materials from the urban mine.

3. Chapter: Methods and Data

In this section, the research approach, method, data acquisition, management and control are discussed.

3.1 Research Diagram

The overall approach for the research is depicted in the following diagram in figure 3.1. The research uses the geographical approach as discussed in the previous chapter. The green blocks represent the steps of the geographical approach, the blue blocks represent individual tasks per each step, the yellow represent the output for the thesis report, and the orange one shows connection to the sub-research questions per step.

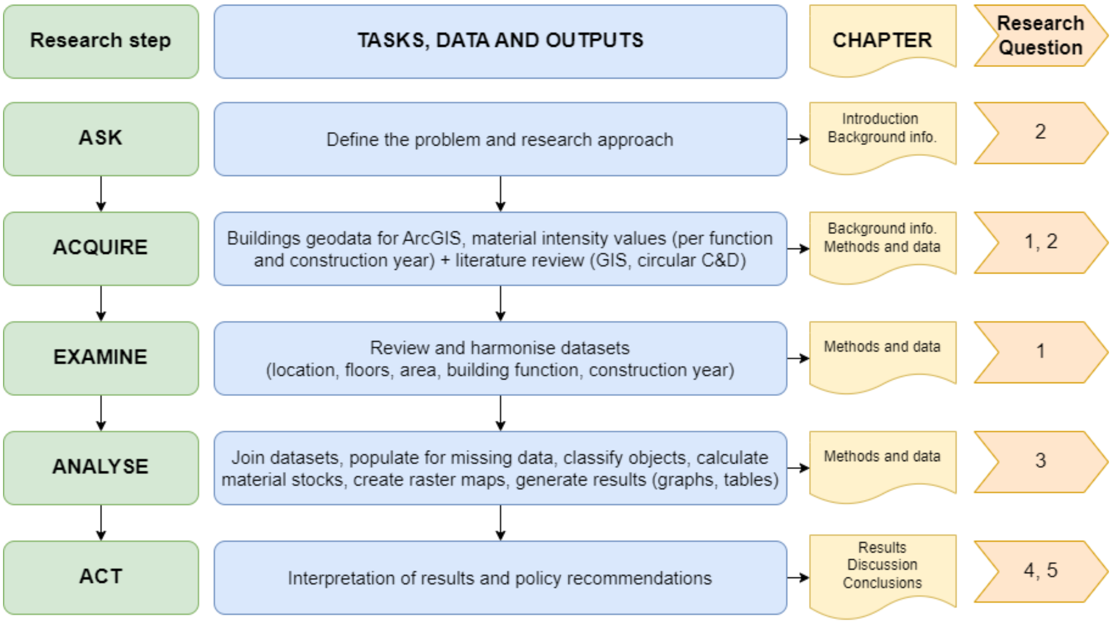


Figure 3.1 Research Diagram

Following is the explanation of the research diagram:

1. Ask – defining the scope of the project (research gap, materials, exact location) and research approach → Introduction chapter and Literature Review chapter (review related to the GIS method)
2. Acquire – acquisition of dataset and data for other attributes (building function, construction year, material intensity), choice of research method, and literature review of concepts and frameworks for circularity in C&D → Methods and Data chapter (research diagram, method and data requirements) and Literature Review chapter (related to the Policy Relevance aspect of the research)
3. Examine – structure and review acquired data, perform conversions, and resolve/populate missing data → Methods and Data chapter (Data Management Plan)
4. Analyse – create data pipeline (steps and sequence) and use ArcGIS tools to produce the desired results → Methods and Data chapter (Data control)
5. Act – generation of maps, tables, and graphs, interpreting results and translating them into actionable items → Results and Discussion chapters

This is the outline of the research, in the next section, the research is broken down using the geographical research method and followed by individual steps of the research.

3.2 Method

In this section, the use of GIS software, material stock research method, and the step-wise process is discussed.

3.2.1 GIS tool and software

GIS stands for geographical information systems, and it is a computer system, which uses data with spatial reference to the surface of Earth. The data have spatial and attribute component, where the former is the *where* and the latter is the *what*. Users can input, store, control, analyse, model, integrate and present data with the use of GIS software.

There are number of alternatives for GIS analysis software. For this research, the ArcGIS was selected, and all analyses were conducted in the ArcMap program. The reasons for the choice of ArcGIS are as follows:

- ArcGIS license is readily available for students and teaching staff at Leiden University
- ArcGIS is an industry standard used by both researchers and professionals
- ESRI, the company behind ArcGIS, provides consistent support and debugging
- Using ArcGIS also allows for an easier transition to practice after the graduation
- Base data for research were provided in the ArcGIS format

3.2.2 Material stock research method

The method applied in this case is based on the approach used in the study by Miatto et al. (2019) and Tanikawa & Hashimoto (2009) for estimating the material stock of the buildings with the use of the GIS bottom-up approach. The objective is to arrive at the total building material stocks of selected materials, which requires data collection, literature review, data management, and analysis.

This method starts with obtaining a dataset of objects (buildings), including the area of the building, number of floors, construction year and the building function. In case the construction year and the building function are missing, these need to be found in other sources and merged with the dataset. An important step in this method is to find material intensities of different materials, which results in a table that defines the material intensity per building function and construction year (or period). Once this table is prepared, material stock per building can be calculated and finally added up to create total results.

Below, the application of this research method is explained in the context of this thesis research. Figure 3.2 depicts the method in terms of required data, flow of data and calculations, which is explained in words below.

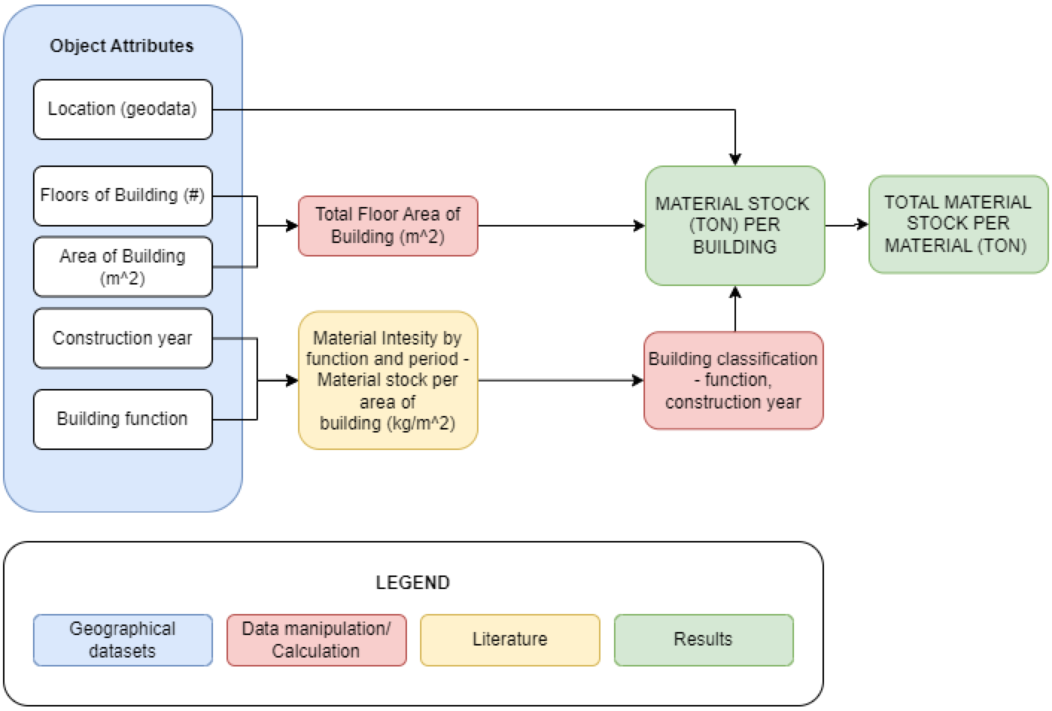


Figure 3.2 GIS bottom-up research method

The individual elements of the method displayed in the diagram above are discussed in the next section and are highlighted in bold. More detailed information about units, data manipulation and calculations are explained further in this chapter.

3.2.3 Method step-by-step

The method discussed in the previous section can be broken down into individual steps as discussed below. This is a general guideline for the individual steps with basic information, and their details and technical procedures are discussed in detail later in this chapter.

1) Collect geographical data
    a. List data requirements
        i. **Geographical datasets**
        ii. **Material intensity data**
    b. Identify data sources
    c. Contact various parties, review existing literature and public sources
    d. Acquire the datasets
2) Review and select data set to work with
    a. Compare and select a geo dataset that contains all necessary attributes (number of floors, building function, construction period) based on size and completeness of the dataset, or combination of multiple datasets
    b. Select data for material intensities or select an alternative source in case data for material intensities in buildings in Czech Republic/Brno are absent
    c. Report characteristics of the data, reason for their choice, assumptions, and limitations
3) Harmonize attributes for material stock calculation

    a. Based on available data for material intensities, categorize buildings into categories represented by combination of construction period and function per each material
    b. Provide explanation, reasoning and calculations used for the harmonization
4) Create one baseline dataset
    a. Combine datasets in ArcGIS to create a baseline dataset (e.g. two datasets with same building objects and complimentary attributes)
    b. Select and apply appropriate projection
5) Adjust building function and construction period
    a. Based on harmonization, adjust the building function and construction period in ArcGIS in the baseline dataset
6) Resolve missing data for construction period (if data for researched location are unavailable)
    a. Apply three different assumptions on how missing data can be populated
    b. Compare and select one of the methods based on the assumptions
7) **Classify each building object** based on its building function and construction period
    a. Assign each building with material intensity value per each material based on the category
8) **Calculate total floor area** of each building
9) **Calculate material stock per object** to create results
10) Rasterize vector layers into raster images
    a. Calculate material stock per object in t/m^2
    b. Rasterize vector layers and aggregate rasters for absolute amounts of materials and average amounts of materials (hotspots)
11) Create maps
    a. Categorize data
    b. Insert description, scale, north arrow, etc.
12) Export data
    a. Split dataset in two
    b. Export data to Excel
    c. Merge data in one Excel sheet
13) **Calculate total material stock per material** and create graphs with other results

3.2.4 Policy relevance approach

The policy relevance aspect of this research is only limited, since its role is not to analyse the governance of the circular C&D in Czech Republic, but more understand how the results can be translated into practical and actionable recommendations for decision makers and relevant actors.

The approach consists of firstly understanding, what circular C&D entails and who are its relevant actors. Secondly, a general overview of challenges that are posed to transition towards circular C&D are presented. Once these are established, the relevant tools that are used for improvement of C&D circularity are discussed, with the aim to identify the usefulness and application of GIS in this matter. This helps to identify which areas of C&D can GIS be used for and whom the results of GIS analysis serve. After that, further look is taken into the identified areas to understand their characteristics and challenges, in order to motivate which barriers could be addressed with GIS analysis. Once the issues within C&D relevant to GIS analysis are identified, review of relevant frameworks and plans for circularity in C&D in Czech Republic is conducted. The policy relevance investigation is concluded by looking trends and barriers of circular C&D in Czech Republic to understand the current situation and progress in this field.

As mentioned before, the policy relevance aspect of this thesis does not set to provide an in-depth analysis of the circular C&D industry in Czech Republic. Therefore, the policy relevance investigation is conducted completely in Chapter 2, namely section 2.2. The findings of this from this review are brought up again in Chapter 6, where the results of the GIS analysis are translated into recommendations for relevant actors of C&D.

3.3 Data Collection

This section describes how the desired data were obtained and evaluated in order to be used in this thesis research.

3.3.1 Data Sourcing and Selection

Following is the list of required data and their units as based on the method described in the previous section:

- Buildings geodata (per each building)
  - Location
  - Number of floors (#)
  - Building area (m^2)
  - Construction year (time period)
  - Building function
- Material intensity (per function and construction period of a building)
  - Concrete (kg/m^2)
  - Bricks (kg/m^2)
  - Mortar (kg/m^2)

For the sourcing of data, three main sources are considered – publicly available data, existing literature (case studies, research papers, etc.), and contacting various parties. Following are the parties that were contacted for sourcing of the required data:

- Ministries (Environment, Regional Development, Industry and Trade)
- Universities (CVUT Prague, VUT Brno, Chemical-technological university Prague)
  - Faculties – architecture, civil engineering, construction
- Architectural/urban planning offices (Czech Chamber of Architects, Institute for Urban Planning Prague, Department of Head Architect Prague, Architect office in Brno – KAM)
- Other organizations/projects (INCIEN, Decompose project, BIMfo, Klokneruv ustav CVUT, Czech Agency for Standardization, DataBrno)
- Czech Statistical Office (national, Prague branch)
- Construction and demolition companies

Next, the available building geodata are described, and the selection and acquisition process is discussed. Several data sets were obtained and examined for their potential use for this research. The names, general description, and sources of the geodata sets are described in table 3.1.

Table 3.1 Geodata sets

Data set name (CZ+ENG)	Description (quoted from the source)	Source
3D model budov (2017) 3D building model	3D building model at this level of detail came to existence in 2020 through photogrammetrical methods from aerial surveying photographs and continued during second phase in 2021. It contains in detail modelled roofs including chimneys, elevetor shafts and airconditioning units with circumferrence of at least 3m and length of at least 2m. Roof towers with circumferrence of at least 8m and height of at least 2m are also modelled. Currently, this dataset contains around 38.000 buildings.	(ArcGIS Hub, 2022)
Orientační model Indicative model	3D model of buildings created by Brno City Chief Architect's Office. The model contains buildings for the whole city and is rather indicative - height of buildings, roof form and roof orientation can differ from reality. The model has been created using 3D Basemaps Solution provided by ESRI and using following data - digital terrain model (2019), digital surface model (2019) and buildings' footprints (February, 2020). It is possible to join data with buildings research.	(data.Brno, 2022a)
Průzkum budov v Brně (2018-2020) Survey of buildings in Brno (2018-2020)	The polygon layer contains information obtained within the survey of buildings in Brno which was held from 2018 till 2020. It represents the results of the first survey about buildings in the city of Brno. The survey focused on the number of floors (above ground), usage of the every floor or type of roofs. Details about the survey can be found here (currently it is available only in Czech). It is possible to join data with indicative 3D building model.	(data.Brno, 2022b)
Stáří budov Age of buildings	Polygon layer that contains buildings based on Building registry (RÚIAN) and Building research in Brno, and construction period of these buildings. The construction periods are based on secondary sources and historical aerial photographes.	Kancelář architekta města Brna. Stáří budov [data file]. Brno, 2019 [cited 2.5.2022] Obtained directly from Architect Office in Brno (KAM) direct contact via email
Stavební objekty Building registry	The Register of Territorial Identification, Addresses and Real Estate (RÚIAN) is one of the four basic registers of the Czech Republic. It concerns complete and accurate accounting of each building on different administrative levels (e.g. municipality, house number and descriptive number, function)	(data.Brno, 2021b)

To decide which of these geodata sets should be used for the research, the geodata sets are compared based on the 1) number of objects (buildings) and 2) completeness of the necessary attributes.

As for the number of objects, the more the better; the objects should be registered on the level of buildings, as compared to objects like building foundation, horizontal/vertical wall. The necessary data attributes for geodata set are number of floors (#), construction year (time period), building function, location and building area (m^2).

Since the location attribute is already a prerequisite of geo data and building area attribute can be calculated based on the geo data, these two attributes do not play a role for the selection of the ideal geodata set for this research. Additionally, the attribute of RÚIAN code is considered in this comparison, which is a registration code of an object connected to the land registry of Czech Republic. This is optional and beneficial, as it would make the dataset readily referable to the national building registry. The overview of the attribute criteria is as follows:

- Number of floors (#) – required
- Construction year (time period) – required
- Building function (function name) – required
- Location (geolocation data) – already included in all geodata hence not considered
- Building area (m^2) – not required as it can be calculated
- RUIAN code (code number) – optional

The different datasets are compared based on their attributes and the number of objects in table 3.2 below.

Table 3.2 Geodata sets comparison

Data set name (CZ+ENG)	Attributes	Number of objects
3D model budov (2017) 3D building model	RUIAN code	1.260.556
Orientační model Indicative model	RUIAN code	127.601
Průzkum budov v Brně (2018-2020) Survey of buildings in Brno (2018-2020)	RUIAN code Number of floors Building function	127.601
Stáří budov Age of buildings	Construction year Building area Building function	127.629

Stavební objekty Building registry	RUIAN code Building function	76.689

Based on the table 3.2, the two geodata sets *Survey of buildings in Brno (2018-2020)* and *Age of buildings* are selected for the research. The reason for selection of these two geodata sets is that they contain almost the same number of objects (127.601 and 127.629), where it has been verified that the 127.601 objects from the first geodata set are overlapping with the second geodata set, which allows for merging of these two geodata sets. Secondly, the required attributes can be covered by the combination of these two geodata sets.

To summarize, the required attributes will be supplied by the data sources as shown in the following table 3.3.

Table 3.3 Selected datasets for the study

Dataset name	**Attributes**
Průzkum budov v Brně (2018-2020) Survey of buildings in Brno (2018-2020)	RUIAN code Number of floors Building function
Stáří budov Age of buildings	Construction year Building area Building function

3.3.2 Description of selected geo datasets

In this section, the selected geodata sets are described in detail. For clarity reasons, only English names will be used from now on.

Survey of buildings in Brno 2018-2020

The survey of buildings in Brno, was carried out between 2018 and 2020 and it was aimed to find out the necessary information about the structure and functional use of individual buildings. The reason was the clarification of information from existing secondary data sources, their updating and the completion of missing or undetected data. The layer contains polygons with attributes such as the number of floors (above ground), usage of every floor, type of roofs and RUIAN code, and it is in a GCS_WGS_1984 projection.Regarding the function attribute, it contains building function for each floor (up to 28 floors), and for the first 2 floors, a percentage is given as to how much of that floor is represented by the given use function. For the sake of reducing complexity, the function of the first floor is taken as the overall function. Additionally, some buildings have a mixed function on the first floor, however, this is also neglected for the sake of complexity reduction. It is believed as plausible to neglected, because for 107.997 records (out of 127,601, cca 85%) the first floor has only one function. For 699 records, the first function occupies 90% of the floor area, for 3.648 records the first function occupies 80%, for 12.574 the first function occupies between 50-70%, and the rest 2.703 the first function occupies 10-40% of the first-floor area.

Age of buildings

The Age of buildings dataset was created for territorial analytical documents, which serve as a basis for the creation of a spatial plan, regulatory plans and changes; furthermore also supportive for decision-making in the territory. It is updated continuously but latest every 4 years. It is comprised of a polygon layer that contains buildings based on Building registry (RÚIAN) and Building research in Brno, construction period of these buildings, and building functions. This dataset layer is in a GCS_WGS_1984 projection.

Completing baseline dataset

Since the choice was made for the use of the two abovementioned dataset, they need to be merged into one baseline dataset, which is explained in the Data Control section. Furthermore, both of these datasets contained the building function attribute, therefore, a choice had to be made as for which source will be used. The *Survey of buildings in Brno (2018-2020)* was chosen over *Age of Buildings* because the latter data set has 39.003 records with missing building function.

In the following sections, the relevant attributes are shown in more detail.

Building Functions overview and characteristic

In the table 3.4, the building functions from the *Survey of buildings in Brno (2018-2020)* dataset are displayed. This provides insights into the dataset in terms of what building functions there are and how are they represented in terms of count and its percentage, and the sum of the area and its percentage as compared to the total dataset. The building functions were sorted based on the count of the total dataset.

Table 3.4 Building functions - overview and characteristics

Function (CZ)	Function (ENG)	Count	% of total dataset	Sum area (m^2)	Percentage area
bydlení	living	62696	49,13%	5357315	34,56%
garáž	garage	21496	16,85%	987200	6,37%
zahrádky	gardens	11282	8,84%	240729	1,55%
maloobchod	retail	3112	2,44%	1149093	7,41%
rekreace	leisure	3037	2,38%	141982	0,92%
sklad, distribuce, logistika	warehousing	2924	2,29%	1506975	9,72%
kanceláře	offices	2602	2,04%	810693	5,23%
jiné specifické využití	other specific use	2323	1,82%	136672	0,88%
služby spotřebitelské	services	2245	1,76%	494593	3,19%
jiné zařízení technické infrastruktury	other tech. infrastructure	1769	1,39%	196367	1,27%
bydleni	living	1365	1,07%	114481	0,74%
stravování	alimentation	1355	1,06%	305483	1,97%
škola	school	1237	0,97%	433082	2,79%
průmyslová výroba	industrial manufacturing	1191	0,93%	580272	3,74%
nerušící výroba, montáže	non-disturbing manufacturing	1025	0,80%	632813	4,08%
garáž nerezidenční	non-residential garage	789	0,62%	166186	1,07%
bez využití	without use	744	0,58%	138353	0,89%
univerzita	university	540	0,42%	204351	1,32%
sportovní zařízení	sport function	519	0,41%	165995	1,07%
ubytování	accommodation	476	0,37%	98983	0,64%
zemědělská a lesnická výroba	agricultural/forestry	418	0,33%	130553	0,84%
jiné zařízení dopravní infrastruktury	other transportation infrastructure	392	0,31%	81936	0,53%
nemocnice, poliklinika	hospital	354	0,28%	129873	0,84%
nevyužívaný komerční prostor	unused commercial space	336	0,26%	72338	0,47%
církevní stavba	religious building	313	0,25%	54358	0,35%
zařízení sociální péče	social care	243	0,19%	64104	0,41%
velkoobchod	wholesale	198	0,16%	170846	1,10%
věda, výzkum	science and research	189	0,15%	70840	0,46%
lékař	doctor	181	0,14%	32113	0,21%
průjezd	passage	169	0,13%	24944	0,16%
úřad	office (governmental)	165	0,13%	49391	0,32%

jiné kulturní zařízení	other cultural facilities	151	0,12%	45164	0,29%
studentské ubytování	student accommodation	144	0,11%	59431	0,38%
jiný objekt veřejné správy	other public administration object	141	0,11%	27636	0,18%
jiné zdravotnické zařízení	other medical facilities	137	0,11%	26968	0,17%
zpracování odpadu	waste processing	113	0,09%	47128	0,30%
víceúčelová zařízení pro kulturu a sport	multipurpose facility for culture and sport	101	0,08%	31385	0,20%
policie	police	94	0,07%	27184	0,18%
armáda	army	86	0,07%	39084	0,25%
čerpací stanice PHM	gas station	84	0,07%	16704	0,11%
památka, hrad, zámek	monument, castle, palace	82	0,06%	20749	0,13%
vozovna	depot	82	0,06%	61048	0,39%
výstavnictví	exhibition	79	0,06%	101464	0,65%
zubař	dentist	78	0,06%	13606	0,09%
hasiči	fire department	71	0,06%	13752	0,09%
parkovací dům	parking house	67	0,05%	100536	0,65%
muzeum	museum	58	0,05%	16301	0,11%
pohřebnictví	funeral services, cemetary	55	0,04%	6494	0,04%
pošta	post office	54	0,04%	17448	0,11%
divadlo	theatre	53	0,04%	21320	0,14%
zoo	zoo	50	0,04%	6333	0,04%
nádraží, stanice	train station/stop	30	0,02%	7220	0,05%
galerie	gallery	29	0,02%	13322	0,09%
soud	law court	24	0,02%	17625	0,11%
letiště	airport	21	0,02%	11893	0,08%
vězeňství	prison	17	0,01%	6876	0,04%
kino	cinema	9	0,01%	2034	0,01%
velvyslanectví	embassy	6	0,00%	1299	0,01%

Construction period overview

In table 3.5, the distribution of construction year period is shown as based on the *Age of buildings* dataset. The table shows a time period, during which a building was constructed, label from the dataset for such period, and count for each period category per object.

Table 3.5 Construction period overview

Period label	Construction Period	Count
0	not in RUIAN	561
1	1919 and older	5455
2	1920-1945	13695
3	1946-1960	3827
6	1961-1990	28223
7	1991-2000	13909
8	2001-2010	8327
9	2011-2020	12597
21	1952 and older	5373
22	1953-1976	1741
99	missing data	33891

Based on this overview, several issues need to be resolved. First, comparing the categories with period label 1-9 and 21-22, some of the construction period categories are overlapping with other categories. Hence, the categories need to be harmonized to remove the overlap of categories. For that sake, the material intensity data are needed first, therefore, this is only addressed later in section 3.3.6 Data manipulation.

Second, categories with the label '0' and '99' represent buildings that do not have assigned a construction period. Three different assumptions are used to populate the missing construction years and their outcomes are compared, which serves as a sensitivity analysis. Based on the comparison, one of the assumptions is selected to be proceeded with. Since this process requires an understanding of the dataset, dataflow and calculations in ArcGIS, this process is only discussed later in section 3.4.3 Missing construction period data.

3.3.3 Material intensity data selection and characteristics

The next data requirement are material intensities for concrete, bricks, and mortar. Unfortunately, the data for Brno, or generally for Czech Republic, were do not exist or they do exist, but were not found. Annex 1 shows an overview of parties that were contacted, and the keywords used for the search of these data among public sources and existing literature.

Since the data for material intensities of buildings in Brno are not available, an alternative source of information had to be used. The alternative source selected for this sake is a case study on Vienna's material stock in buildings. In the following paragraphs, it is explained, why this alternative source was chosen. The selection of an alternative source of data is based on an already existing database compiling material intensities (and other characteristics) of case studies from different regions, countries, and cities (Heeren & Fishman, 2019).

First, the choice of alternative sources had to be narrowed down to case studies on cities that would be most likely relatable to the characteristics of buildings and the material stock of buildings in Brno, Czech Republic. The considered countries and regions were narrowed down to this list, as based on the case studies listed in the abovementioned database:

- Germany
- Poland
- Slovakia
- Austria
- Central Europe (Belgium, The Netherlands, Ireland, Hungary, Slovenia, Luxemburg, Germany, United Kingdom, Slovakia, Denmark, Czech Republic, Austria, Poland)

The reason for considering these countries is that they are neighbouring countries to Czech Republic, or in its vicinity. The data for Germany, Poland and Slovakia are not suitable due to their limited data (too few data entries, missing material intensities of sought materials, missing construction periods), and the data for Central Europe are not suitable due to the data coming from too broad geographical scope and missing data for non-residential buildings. The data found in a study on Vienna, Austria (Kleemann et al., 2017), are considered sufficient because they are complete, and they cover the same or similar (overlapping) construction periods as the dataset for Brno. The dataset has also entries for both residential and non-residential buildings, as well as the three selected structural materials – concrete, bricks and mortar. Vienna also represents the most similar architectonic and construction style to Brno, as these two cities are relatively near (140 km away) and have been historically united under the same administrative region up until the year 1918. On the other hand, the urban planning and architectonic style of buildings in Brno might differ from the style in Vienna since 1948 due to the communist regime in Czech Republic. However, the Vienna dataset still represents the most suitable alternative for Brno due to relative similarity and data availability as explained above. Additionally, the Vienna study considers numerous case studies; based on a brief review of several of these case studies, it was found that the material intensity data for Vienna also consider panel houses, which are relevant for Brno due to abundant residential panel house estates in Brno.

The Vienna study aggregates several single real-world case studies sourced from construction files, individual case studies, and LCA data, and spans between period 1900 to present. The periods considered in the Vienna case study are following:

- 1900 – 1918
- 1919 – 1946
- 1947 – 1977
- 1977 – 1997
- 1998 – present

This dataset has material intensity values for ‘residential’, ‘commercial’ and ‘industrial’, however, for some periods values of the ‘industrial’ building function are missing. Therefore, we consider building function ‘residential’ for the residential buildings, and ‘commercial‘ for the non-residential buildings of in the Brno dataset.

Having found the geo datasets with the building objects, functions, construction periods, along with using an alternative source for the material intensities, all the required data were collected. In the next sections, it is discussed how these data were harmonized in terms of matching the construction period and building functions of the Brno dataset to the material intensities of the Vienna dataset.

3.4 Data Processing

The overarching need to adjust some of the attributes from the original geodata set of building objects in Brno comes from the lack of data on material intensities for different combinations of 1) construction time period, 2) building function, and 3) selected materials. For that sake, the original geodata set for Brno will use the material intensity data from the Vienna study. This requires matching the building functions and construction time periods from the Brno geo dataset to the data in the Vienna study in order to utilize the material intensities data applied in the latter study.

3.4.1 Assignment of building function

Firstly, the different functions in the dataset for Brno are narrowed down to either residential or non-residential buildings. The following table 3.6 demonstrates the allocation of individual building function attribute values and the reasoning behind it is given under the table.

Table 3.6 Building function typology assigment

Function	Function (ENG)	Assigned typology
bydlení	living	residential
garáž	garage	other
zahrádky	gardens	other
maloobchod	retail	non-residential
rekreace	leisure	non-residential
sklad, distribuce, logistika	warehousing	other
kanceláře	offices	non-residential
jiné specifické využití	other specific use	non-residential
služby spotřebitelské	services	non-residential
jiné zařízení technické infrastruktury	other tech. infrastructure	non-residential
bydleni	living	residential
stravování	alimentation	non-residential
škola	school	non-residential
průmyslová výroba	industrial manufacturing	non-residential
nerušící výroba, montáže	non-disturbing manufacturing	non-residential
garáž nerezidenční	non-residential garage	other
bez využití	without use	non-residential
univerzita	university	non-residential
sportovní zařízení	sport function	non-residential
ubytování	accommodation	residential
zemědělská a lesnická výroba	agricultural/forestry	non-residential
jiné zařízení dopravní infrastruktury	other transportation infrastructure	non-residential
nemocnice, poliklinika	hospital	non-residential
nevyužívaný komerční prostor	unused commercial space	non-residential

církevní stavba	religious building	other
zařízení sociální péče	social care	non-residential
velkoobchod	wholesale	non-residential
věda, výzkum	science and research	non-residential
lékař	doctor	non-residential
průjezd	passage	other
úřad	office (government)	non-residential
jiné kulturní zařízení	other cultural facilities	non-residential
studentské ubytování	student accommodation	residential
jiný objekt veřejné správy	other public administration object	non-residential
jiné zdravotnické zařízení	other medical facilities	non-residential
zpracování odpadu	waste processing	non-residential
víceúčelová zařízení pro kulturu a sport	multipurpose facility for culture and sport	non-residential
policie	police	non-residential
armáda	army	non-residential
čerpací stanice PHM	gas station	other
památka, hrad, zámek	monument, castle, palace	other
vozovna	depot	non-residential
výstavnictví	exhibition	non-residential
zubař	dentist	non-residential
hasiči	fire department	non-residential
parkovací dům	parking house	other
muzeum	museum	non-residential
pohřebnictví	funeral services, cemetary	non-residential
pošta	post office	non-residential
divadlo	theatre	non-residential
zoo	zoo	non-residential
nádraží, stanice	train station/stop	non-residential
galerie	gallery	non-residential
soud	law court	non-residential
letiště	airport	non-residential
vězeňství	prison	residential
kino	cinema	non-residential
velvyslanectví	embassy	non-residential

All buildings with a function related to housing, sheltering and accommodation of people are considered residential, this also includes student housing and prisons. Any other buildings were considered as non-residential with the exception of the listed types followed by explanation below:

- Garden – not representing a building, but a space that might have some structures around or within it
- Warehouse – typically consisting of diametrically different materials than both residential and non-residential buildings
- Religious building – atypical structures and shapes, often large and spacious however this cannot be reflected in number of floors as used in the methodology of this research
- Passage – more or less empty space

- Gas station – often made of different materials than both residential and non-residential buildings
- Monument, castle, palace - atypical structures and shapes, often large and spacious however this cannot be reflected in number of floors as used in the methodology of this research
- Garage, non-residential garage and parking house – specific material composition, almost no loadbearing walls
- Recreational – atypical structures and shapes, which would add more complexity

3.4.2 Transformation of construction periods

Secondly, the construction time periods of the Brno data set have to be transformed into the construction time periods of the Vienna data set. The scheme in table 3.7 demonstrates how the original time periods were transformed into the new time periods of the Vienna data set. This allocation is based on a rule, where the new construction period is based on the number of overlapping years of the original and the new time period. For instance, if the original period is 1946-1960, then it is allocated to the time period 1947-1977, because most of the years overlap. Similarly, if the original period is 1991-2000, then it is allocated to the time period 1977-1997. Please, see Annex 2 for more detailed information and data operations behind the construction period transformation.

Table 3.7 Construction period data transformation

Original label	Original period (Brno dataset)	New label	New period (Vienna dataset)
0	Not registered in RUIAN	6	missing
1	1919 and older	1	1900-1918
2	1920-1945	2	1919-1946
3	1946-1960	3	1947-1977
6	1961-1990	3	1947-1977
7	1991-2000	4	1977-1997
8	2001-2010	5	1998-present
9	2011-2020	5	1998-present
21	1952 and older	2	1919-1946
22	1953-1976	3	1947-1977
99	missing data	6	missing

The manipulation of building function and the construction period as described in this section are prepared prior to any editing of the dataset in ArcGIS. Once the new building function and the new construction period are assigned, these changes are implemented in the attribute table of the dataset, which is explained in the Data Control section.

3.4.3 Material Intensity table

Based on these assigned functions and transformed construction periods, each combination can be assigned a material intensity value (kg/m^2) per each material. In table 3.8, one can see the values for concrete, bricks, and mortar for residential, non-residential and other objects, per each period.

Table 3.8 Material Intensity table

		CONCRETE	
	Function label	1	2
	Function	Residential	Non-residential
Period label	**Period**		
1	1900-1918	134,6	170,6
2	1919-1946	455,2	786,8
3	1947-1977	748,8	1276,7
4	1977-1997	827,9	1392,0
5	1998-present	1138,7	1299,1
		BRICKS	
	Function label	1	2
	Function	Residential	Non-residential
Period label	**Period**		
1	1900-1918	925,4	1098,9
2	1919-1946	542,4	636,3
3	1947-1977	426,3	258,1
4	1977-1997	533,8	20,2
5	1998-present	119,6	22,2
		MORTAR	
	Function label	1	2
	Function	Residential	Non-residential
Period label	**Period**		
1	1900-1918	301,8	323,9
2	1919-1946	217,4	211,1
3	1947-1977	158,0	78,8
4	1977-1997	177,9	4,7
5	1998-present	13,5	35,6

The values are based on the case study from Vienna as discussed earlier. The specific values are arrived at by taking an average of all available values for a given period, function, and material. To demonstrate, if there would be three entries available for concrete in residential buildings between 1900-1918 with values 100, 125, and 150 kg/m^2, the value used for the material intensity is 125 kg/m^2.

In the case of non-residential buildings during period 3 (1947-1977), the data for material intensity were missing for all three materials. Estimation for this period was calculated based on the following calculation:

1) A ratio (T) between material intensity value of residential (r) and non-residential buildings (n) was calculated for each material (x) and period (y) that had existing values.
   → $T_{XY} = MI_{RXY} / MI_{NXY}$
2) Non-residential buildings from period 3 had no have material intensity values, therefore, ratio (T) could not be calculated in the previous step. The ratio for non-residential buildings in period 3 (T_{X3}) was therefore calculated with use of other ratios. The ratios of period 2 and 4 are added up and divided by 2 for each material.
   → $T_{X3} = (T_{X2} + T_{X4}) / 2$
3) Once the ratio for each material in period 3 was calculated, the material intensity of non-residential buildings in period 3 is calculated for each material (MI_{NX3}).
   → $MI_{NX3} = T_{X3} * MI_{RX3}$

Building function 'other' is excluded from the research, hence, it is not presented in the table. The exact calculations for each of the values in table 3.8 are shown in Annex 3.

Having the material intensity table ready marks the next step, where the various operations on the dataset can be done in order to obtain results, which is explained in the next section.

3.5 Data Analysis

In this section, the various data operation and analysis tools applied in ArcGIS to obtain results are explained in a chronological order. This pertains to the following steps:

1) Merging the two geo datasets to create a baseline dataset
2) Adjustment of building function and construction period in the dataset
3) Population of missing construction period data

3.5.1 Baseline dataset

The first operation is to merge the *Survey of buildings in Brno 2018-2020* and the *Age of buildings* dataset to create the baseline dataset. Additionally, a projection is chosen to be later able to display a realistic projection of the curved shape of the Earth onto a 2D surface, i.e. map. Following is the procedure:

1. Use 'Spatial Join' function in ArcGIS
2. Select the two datasets *Survey of buildings in Brno 2018-2020* and the *Age of buildings*
3. Join operation: JOIN_ONE_TO_ONE
4. Match option: INTERSECT
5. Review whether the 'Spatial Join' operation was successful (i.e. expected number of records, attributes from both datasets matched)
6. Use the 'Project' tool in Data Management → Projections and Transformations to select a projection of the dataset.
7. Choose projection 'S-JTSK_Krovak_East_North'. This projection has been tested on the dataset and is considered suitable, as it maintains realistic dimensions of objects (i.e. 1m x 1m tile has a square shape on the map).

3.5.2 Building function and construction period

Next, building function and construction period attributes are adjusted in the attribute table based on the harmonization explain in the previous sections as follows:

1. Create a new field attributes for building function (*func_class*) and construction period (*period_cla*)
2. Remove special signs (typical in Czech language) from the original building function attribute without which further calculations would result in an error
    i. Choose table options and use the 'Find and Replace' function
    ii. Replace function names with a name not containing special symbols (e.g. *ubytování* → *ubytovani*)
3. Run the field calculator to assign the new building function based on the harmonization, which allocates number 1 to residential buildings, 2 to non-residential, and 3 to others (see Annex 4 for the exact Python script in ArcGIS field calculator)
4. Remove objects with label 3 (other functions) in order to reduce the calculation time
5. Run the field calculator to assign the new construction period based on the harmonization, which allocates allocate label numbers to respective time periods (see Annex 5 for the exact Python script in ArcGIS field calculator)
6. Validate whether all records in the attribute table have been assigned a new (and correct) value

3.5.3 Missing construction period data

Out of the total 87.358 records (after the reduction of records in the previous section), 16.769 of records (19,2% of the dataset) are not assigned any construction period. Three different assumptions were considered to assign the construction period to the objects with missing data.

1) Objects with missing data are assigned the earliest construction period (1900-1918)
2) Objects with missing data are assigned the most recent construction period (1998-present)
3) Objects with missing data are assigned the construction period based on the construction year of the objects in their proximity.

The three assumptions serve as a sensitivity analysis, which tests to what extent the results differ using each assumption. The reason to choose these three assumptions is that results arrived at by using assumptions 1) and 2) would represent the extreme minimum and maximum of the results. Results using assumption 2) would fall somewhere between the results using assumption 1) and 2), and therefore represent probably the most realistic results.

Assumption 1 and 2

Assumptions 1) and 2) are rather straightforward, as the construction year period is directly assigned to the period 1900-1918 for assumption 1, and to the period 1998-present for assumption 2. The process is as follows:

1. Create a new field attribute for the first (periodT1) and second assumption (periodT2)
2. Use the field calculator and follow the Python script as described in Annex 6

Assumption 3

Assumption 3 assigns the construction year period based on the construction year period of the objects in their proximity, which requires data manipulation and analysis tools in ArcGIS. The following data flowchart in figure 3.3 shows the necessary steps for assigning the construction year period to the objects with missing data.

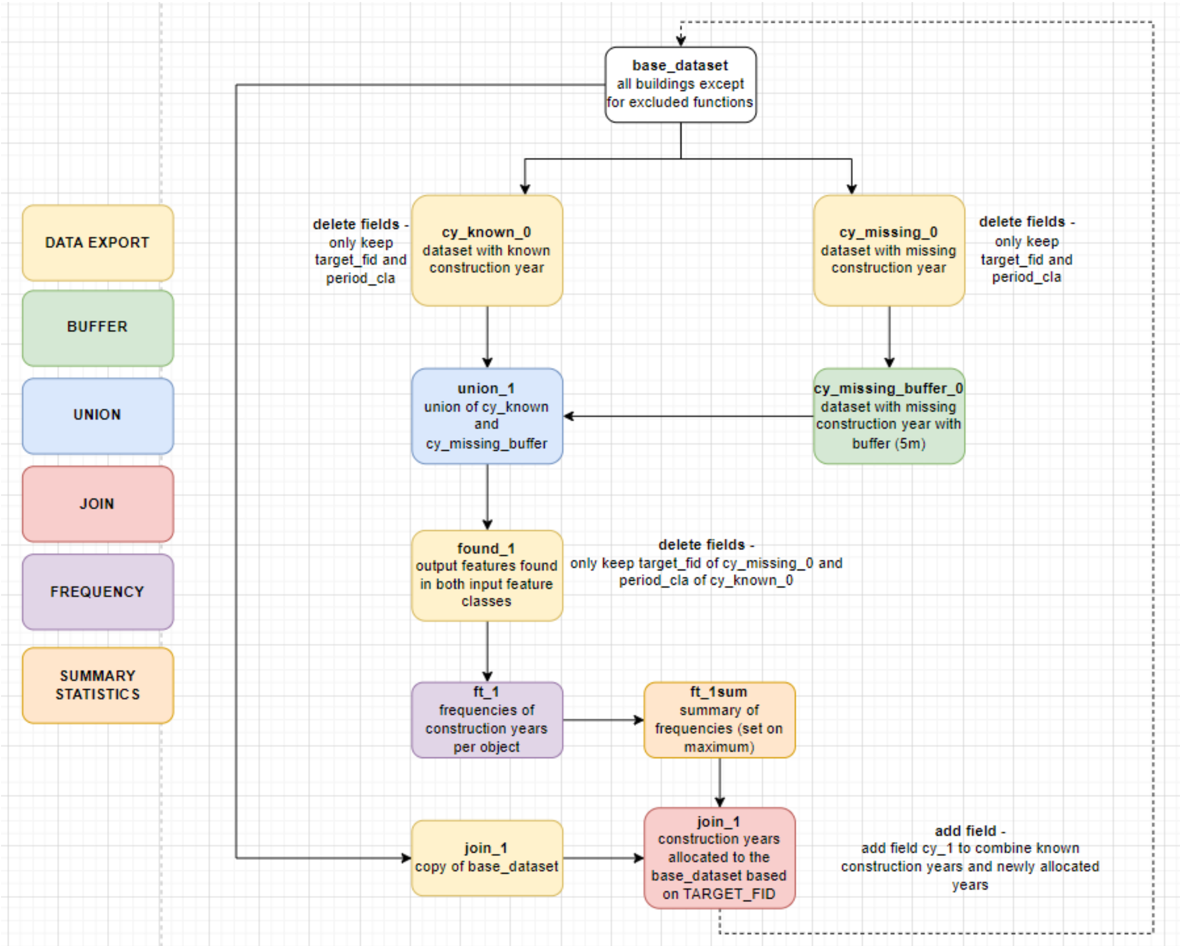


Figure 3.3 Data manipulation for assigning missing construction year period based on object proximity (own creation)

The process shown in figure 3.3 is explained in the following bullet points:

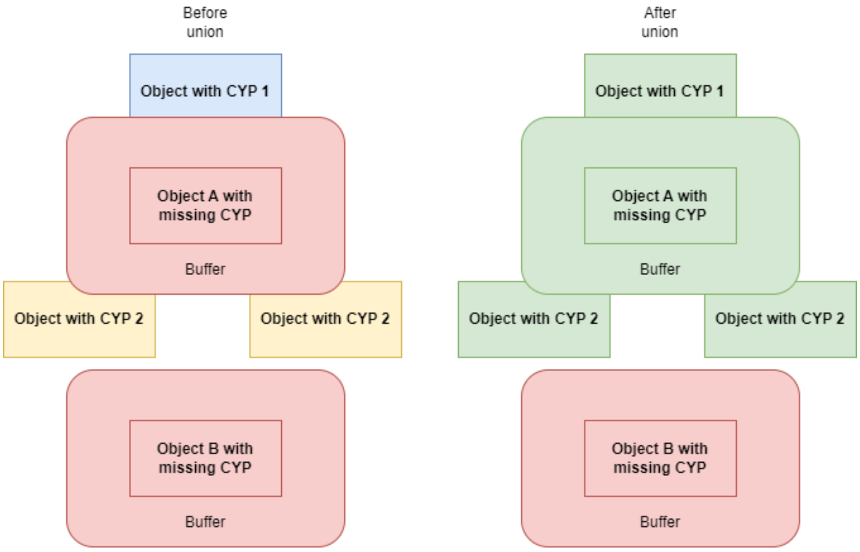
1) Split the total dataset *(base_dataset)* into two datasets - objects with a) known construction year period (*cy_known_n*) and b) missing CYP (*cy_missing_n*)
2) Create buffer for objects with missing CYP (*cy_missing_buffer_n*). Initial buffer is set to 5m but the buffer size increases with further iterations – see step 9 and table x below for overview of buffer sizes for each iteration step.
3) Apply union function to *cy_known_n* and *cy_missing_buffer_n* with gaps not allowed to create *union_n+1*
4) Export overlapping objects from *union_n+1* (i.e. objects of union found in both input feature classes) into *found_n+1*
5) Apply frequency analysis function to *found_n+1* to create a table *ft_n+1* with allocated CYPs and frequencies of each allocated CYP
6) Apply summary statistics (set to max) to *ft_n+1* to create a table *ft_n+1sum* that allocates unique CYP to objects with missing CYP that were found when applying union based on the CYP, which frequency was the highest
7) Join the *base_dataset* with the *ft_n+1sum* based on TARGET_FID to allocate CYP to objects with missing CYP
8) Use the field calculator and follow the Python script in annex 6 to allocate the new CYP in the following manner:

a) Objects with known CYP keep the same CYP
b) Objects with missing CYP are allocated a new CYP if there was a union between the object and *cy_known_n* in step 3
c) Objects with missing CYP remain with missing CYP if there was no union between the object and *cy_known_n* in step 3

9) Review the number of objects with newly allocated CYP after each iteration, if the number of newly allocated objects is too low (cut-off set at 600 new allocations per iteration) buffer should be increased in the next iteration. The increase in the buffer size is determined based on a brief inspection of objects that are still missing CYP and their distance to the closest object with known CYP.
10) Repeat steps 1-9 with the updated *base_dataset* until there are no objects with missing CYP in the *base_dataset*.

For a better understanding, steps 3-6 are visualized in figure 3.4 below. In the figure, one can see that the buffer of object A had an overlap with other objects before the union operation and object B did not have an overlap with other objects before the union operation in step 3. Therefore, the object B will not be assigned a new construction year period. The object A overlapped twice with objects with CYP 2 and once with object with CYP 1, which is summarized in steps 4 and 5. Since object A had more overlaps with objects with CYP 2, it will be assigned with CYP of 2 (step 6).

Figure 3.4 Visualization of the assingmnet of construction period with the use of buffers and union function



Following this iteration leads to the assignment of the construction year period to all objects with missing data. In table 3.9 below, the individual iterations are described as to how many objects are assigned with a construction year period and what buffer sizes were used per iteration.

Table 3.9 Construction year assignment to objects with missing data

Iteration	Known objects	Missing objects	% of missing objects	Assigned during last iteration	Applied buffer size to create union for this iteration [m]
baseline	70589	16769	19,2%	-	-
1	78483	8875	10,2%	7894	5
2	81272	6086	7,0%	2789	5
3	81939	5419	6,2%	667	5
4	82130	5228	6,0%	191	5
5	84404	2954	3,4%	2274	15
6	84910	2448	2,8%	506	15
7	86045	1313	1,5%	1135	30
8	86247	1111	1,3%	202	30
9	86783	575	0,7%	536	60
10	87085	273	0,3%	302	120
11	87200	158	0,2%	115	240
12	87338	20	0,0%	138	1000
13	87358	0	0,0%	20	4000

Several assumptions were employed to decide the buffer sizes. To avoid a large number of iterations, a cut-off value of at least 600 newly assigned objects per iteration was established, which represents about 3,5% of the missing objects, or 0,7% of the total number of objects in the dataset. This means that once an iteration yields less than 600 newly allocated objects at a given buffer size, the buffer size will be increased for the next iteration. Following is the explanation of the chosen buffer sizes once iterations reached the cut-off value.

For the first iteration, the buffer size of 5m was chosen, as that seemed like a sensible value that would work for the distance between separated/detached houses.

After iteration 4, only 191 objects were assigned a new construction year period, therefore the buffer size was increased. The reasoning is that after a brief inspection, several cases were observed where objects on one side of the street had a known construction year period but all objects on the other street were missing a construction year period. In such cases, the distance between the objects on one side of the street and the opposite one was about 14m, hence a buffer of 15m was chosen.

After iteration 6, only 506 objects were assigned a construction year period, therefore the buffer size was increased. The reasoning after an inspection of the distances between the objects in the dataset was that some objects were further away than just across the street, often at a distance of about 20-25m, hence a buffer of 30m was chosen.

After iteration 8, only 202 objects were assigned a construction year period, therefore, the buffer size was increased. Similar as in previous adjustments, objects were found at a further distance than before, therefore a double value of 60m was chosen.

Iterations 9-13 did not yield more than 600 newly assigned objects, therefore the buffer size was increased during each iteration, namely doubled in iterations 10 (120m) and 11 (240m), a quadrupled in iterations 12 (1000m) and 13 (4000m). These increases were decided based on inspections of the last missing objects, often being objects stranded at the edge of the district or located on a hill, which would place them at a further distance.

Assumption testing and selection

These three assumptions were used to generate three separate datasets, which now have populated missing data for the construction year each based on one of the assumptions. Results can be generated for a total material stock for each material using these three datasets, which allows for comparison of the results and serves as a sensitivity analysis.

Based on this process, assumption 3 was selected as it produces the most realistic results given the assumptions discussed in this section. The comparison of the assumptions and the limitations of the use of these assumptions are elaborated in Chapter 5 under section 5.1.2 Research Assumptions and Limitations.

3.5.4 Categorize the records

Based on the material intensity table, each record can be categorized based on a combination of the building function and construction year, giving it material intensity values for each material:

1. Create three new field attributes for material intensities of each material – concrete (C3_MI), bricks (B3_MI), and mortar (M3_MI)
2. Use the field calculator to assign the material intensity values by following the Python script in Annex 7.

3.5.5 Calculate material stock per object and material

Now that material intensity values are allocated, the amount of material per object can be calculated:

1. Create three new field attributes for the amount of material per each material – concrete (C3_AM), bricks (B3_AM), and mortar (M3_AM)
2. It is calculated as *material intensity value* * *surface area* * *number of floors* per each material using the field calculator and following the Visual Basic in Annex 8.

3.5.6 Rasterization

In order to visualise the material stock of the city, a rasterization process will be carried out. In this process, the vector layer is converted into a raster image. However, as a precursor for this step, it is better to calculate the material intensity per object per square meter to avoid the misinterpretation of the data and convert the amounts into tonnes. The reasoning is explained along with the rasterization process.

1. Create three new field attributes for amount of material per square meter for each material – concrete (ctm2), bricks (btm2), and mortar (mtm2)
2. Use the field calculator and follow the Visual Basic script in Annex 9.

The rasterization process comprises two steps:

1. Turning polygons to raster using the 'Polygon to Raster' tool
   a. Cell assignment type: CELL_CENTER
   b. Cellsize: 1
2. Aggregating raster cells using the 'Aggregate' tool
   a. Use aggregation technique SUM
   b. Cell factor: 100

The first step takes an attribute value of a polygon as an input, and the output is a raster cell with the value of the attribute. The second step generates a reduced resolution of a raster, which takes the raster cells from the previous steps and aggregates them based on an aggregation technique (sum, average, max, min). The idea is to create a raster with cells of 100 x 100 m, which is an appropriate resolution for the size of the location.

In the first step, the values for each material in t/m^2 are the input, and the output is a raster with cells of size 1, which in this case results in a 1x1m cell because the layer is in a metric projection. The reason why we converted material amounts of buildings into t/m^2 is that if we use the value of the total amount of one material in a building, each cell would carry this value, and a building will have as many cells as is its surface area. To demonstrate, a building with a surface area of 12m^2 will have 12 cells of 1 meter. In this way, the resulting rasters would inflate the values displayed on the maps. Conversely, using the amounts per square meter results in each cell carrying the value for all floors but only for one square meter.

In the second step, the raster cells are aggregated to produce maps that are easy to read with the SUM technique. The sum technique generates a raster that sums up all the amounts of material within the gridcell. Using the sum technique is useful for gaining insights into absolute amounts of materials that are there to gain, as it reflects more exactly the amounts of materials based on the number buildings in that cell. This operation utilizes the cell factor of 100, as that is the factor that will multiply with the input raster cells, producing 100 x 100m cells, i.e. 100m^2. Finally, legend and descriptions are added.

This way, a set of 3 maps was created which is analysed in the Results chapter.

3.5.7 Create maps

Finally, rasters can be turned into maps, which is done by selecting each raster layer and categorizing the data first. The quantized categorization method is selected, as this method generates categories with a similar number of elements, which has a certain impact on the interpretation of results, which is discussed in the Results chapter. Next, category labels are reviewed for labels that are handy for maps. After that, we can switch from the Data view to the Layout view, and insert the title, scale, north arrow, and legend. Then, maps can be individually exported via the 'Export map' function.

3.5.8 Data export

The final dataset has 87.358 records, and to create tables, and graphs, and analyse the results, data need to be exported into Excel. Due to the limitation of ArcGIS, it is unable to export more than 65.535 lines of data to Excel, and the following error is generated:

'*ERROR 001531: Input table exceeds the 65535 rows limit of the .xls file format*.'

Workaround for this error is following this procedure:

- Split the dataset in two halves by exporting each half into a separate shape files
    - Select less than 65.535 rows in the attribute table
    - Save as a shapefile
    - Use the 'Table to Excel function' to export the data from this separate layer into Excel
    - Repeat for the other half of the final dataset
- This will generate two Excel sheets in the '.xls' format, however, simply pasting data from one of the Excel sheets to another will not work
- The two exported data Excel sheets must be saved as the '.xlsx' format, and then the data from both of the Excel sheets can be pasted into one '.xlsx' Excel sheet.

Afterwards, a pivot table can be created to generate results in the form of tables and graphs, which are displayed in the next chapter.

3.6 Data Management

This section explains how data are managed in terms of software, files and formats.

Data processing of construction periods and material intensities are first reviewed and transformed in MS Excel. Once the final material intensity and construction period table are prepared, their values are used for calculations in ArcGIS as explained in section 3.4.

All geodata are managed in ArcGIS software. Both polygon shape (.shp format) files '*Survey of buildings in Brno 2018-2020'* and the '*Age of buildings'* are loaded into one ArcMap document (.mxd format) file. After these two shape files are merged into one shape files, it represents the top layer of the data frame.

The ArcMap document uses the polygon shape file '*CZE_Boundaries_2021*', namely the '*CZE_Postcodes5*' subtype from an external GIS server (ESRI, 2022), which shows all city districts of Czech Republic, as a background layer. On top of this layer, as another background layer, is polygon shape file '*hranice_mc_polygons*' (Statutární město Brno, 2021), which displays city districts of Brno Statutory City.

All intermediate files are stored in one geodatabase (.gdb format) file to prevent errors and reduce the calculation times. This geodatabase is not provided along with the submission.

Raster maps are stored in the File GeoDatabase Raster Dataset format and the results of the GIS data analysis process are stored in a shapefile '*final_dataset*', which together form the final results. The final results are delivered as ArcGIS map package (.mpk format) file '*MS_Brno.mpk'* including the background shapefiles and original dataset shapefiles.

The data of the '*final_dataset*' are also exported to MS Excel file 'MS_Brno.xlsx', which also contains material intensities table, construction period data and conversions, graphs, calculations, and other relevant information.

This files '***MS_Brno.mpk**' and* '***MS_Brno.xlsx**'* are submitted along with the thesis report, and can be made available upon the discretion of data.brno and Architect office in Brno, since they are the main providers of the data.

4. Chapter: Results

In this section, the generated results are presented and discussed. First, several graphs are presented to provide insights into the material stock of buildings from different perspectives. Second, raster maps are presented to provide insight into the spatial distribution of the material stock.

4.1 Material stock results

In this section, four graphs are presented that provide an insight into the material stock of buildings in Brno, such as material stock based on building function, construction year, material stock in proportion to function and average material composition per building. The dataset, tables and calculations that were used to create these outcomes are discussed in Annex 10.

4.1.1 Material stock in residential and non-residential buildings

The total material stock of concrete, bricks and mortar per function is shown in figure 4.1. It shows, that the material stock is dominated by concrete with 15.022.934 tons in residential buildings and 19.441.195 tons in non-residential buildings. Concrete is followed by bricks and mortar, which are conversely more represented in residential buildings with 9.482.083 tons of bricks and 3.388.065 tonnes of mortar, as compared to non-residential buildings with 6.790.535 tons of bricks, and 2.260.851 tonnes of mortar.

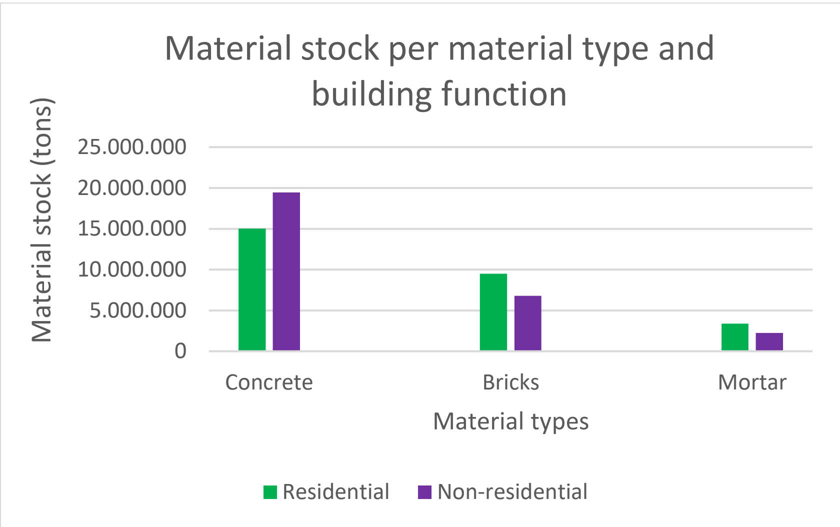
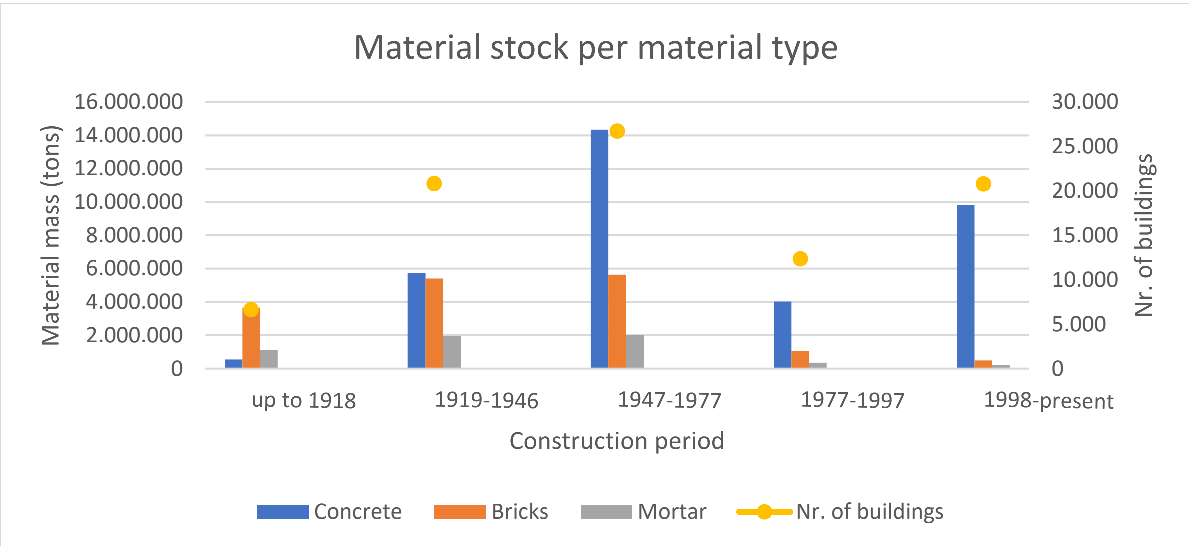


Figure 4.1 Material stock per material type and function class

4.1.2 Material stock across different construction periods

Figure 4.2 displays the material stock per material type in different construction periods. This figure demonstrates the distribution of material types across the existing material stock in the different building age groups, additionally, it shows the number of buildings from these periods on the second vertical axis. Most of concrete is stored in buildings from the period 1947-1977 and in the most recent period from 1998. Most of bricks is stored in buildings in the first three periods, and most of mortar in the period 1919-1946 and 1947-1977, while relatively little of these two materials is stored in the two most recent periods.

The largest material stock is in buildings from the period between 1947-1977, which also represents the highest count of buildings among the different periods (26730 buildings). There is almost the same count of buildings in periods between 1919-1946 (20832 buildings) and 1998 till present (20794), however the former contains more material stock. Similar amounts of materials is stored in buildings up to 1918 and 1977-1997, however the latter has almost double the building count (12359 buildings) as compared to the former (6643).



4.2 Material stock per material type across different construction periods

4.1.3 Material stock composition in proportion to building function

In figure 4.3, one can see how material composition compares to the ratio of residential and non-residential buildings across different construction periods. It can be observed that non-residential buildings represent the majority of material stock from the period up to 1918, between 1919-1946, and the most recent period since 1998. Residential buildings represent the majority of material stock in the period between 1947-1977 and 1977-1997. Additionally, the ratio of concrete in the material stock steeply rises across the time periods, while bricks and mortar maintain relatively stable amounts until the end of 1947-1977, after which their ratio in the material stock shrinks rapidly.

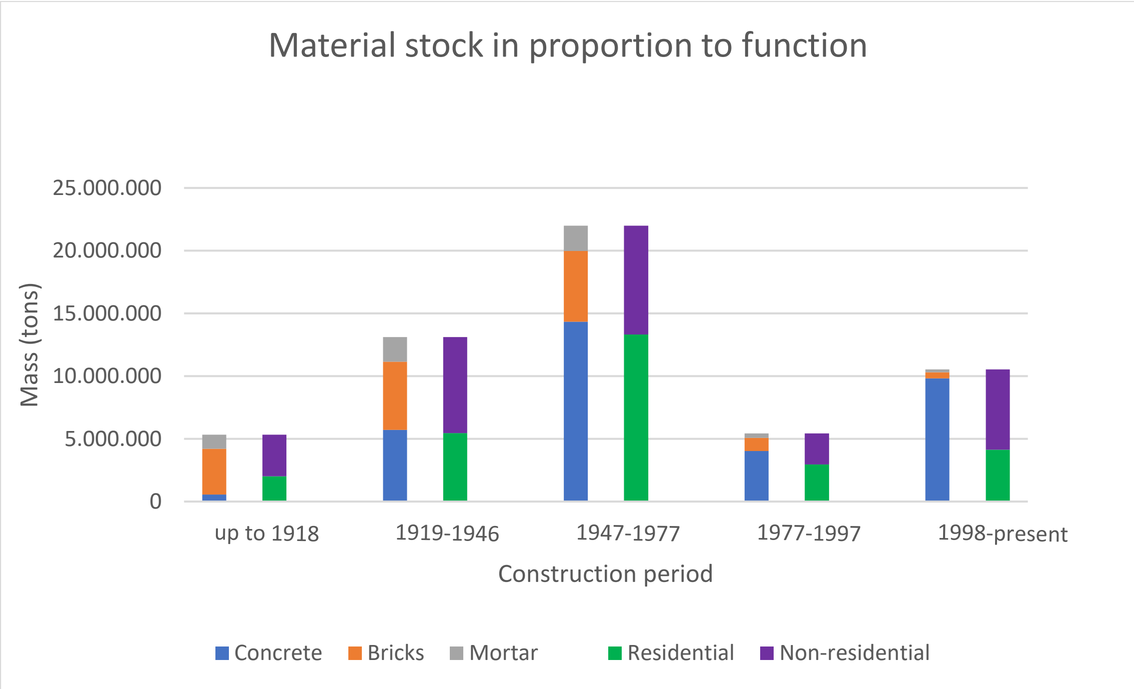


Figure 4.3 Material stock in proportion to function

4.1.4 Average building composition per building function

Figure 4.4 depicts the average building composition per building function, where the left bar in each period shows the residential function and the right bar shows the non-residential function. Additionally, this graphs shows the average number of floors per building function in each time period. The average material stock in non-residential buildings declines across the time, while residential buildings maintain a relatively stable average amount of materials with the exception of the 1947-1977 period. For both building functions, the proportion of concrete increases over time, with bricks and mortar being practically phased out in the last two periods in the non-residential buildings and playing a minor role in residential buildings since 1998.

For residential buildings, the average number of floors rose from 2,4 in 1918 to 3,1 in 1947-1977, after which it stabilizes at an average of 2 floors since 1977. The non-residential buildings experienced a decline in the average number of floors from 3,7 in 1918, to 3 in 1919-1946, and stabilizes at 2,1 floors since 1947. Depicting the average number of floors in relation to the average material composition is relevant for understanding material efficiencies.

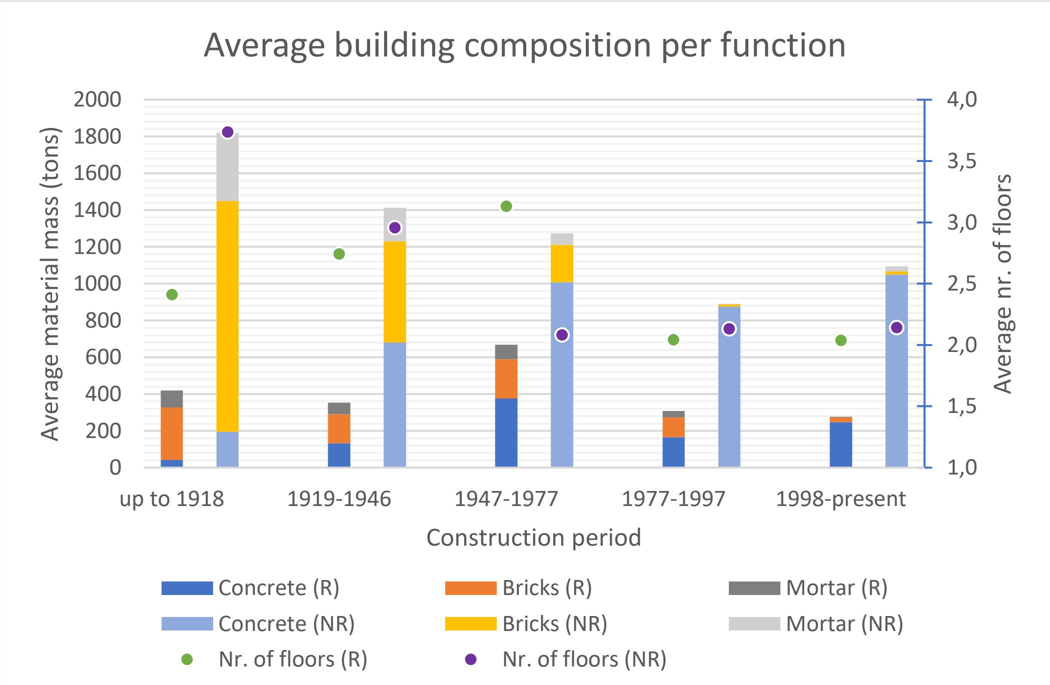


Figure 4.4 Average building composition per function

4.2 Raster maps

In this section, raster maps from the GIS analysis are shown. First, the spatial distribution of buildings by construction period is shown for the dataset with populated data, where data were previously missing. Secondly, the spatial distribution of buildings by function is shown. Lastly, three maps demonstrate the spatial distribution of absolute material stocks for each material, resulting in 3 maps.

4.2.1 Spatial distribution of buildings by construction year

Figure 4.5 shows the map displaying the spatial distribution of the building construction period. It is using the dataset that has populated the missing construction period based on the assumption discussed in Chapter 3. A map that displays the spatial distribution of the building construction period with missing data can be found in Annex 11.

Buildings from the period up to 1918 (purple) are mainly concentrated in the very centre of the city. Buildings from the next period, 1919-1946 (green), surround the centre and stretch also stretch across the northwest, north, and northeast of the extended city centre. Buildings from the period 1947-1977 (red) lie behind the borders of the extended city centre, and some groups of buildings are even further away, completely disconnected from the city sprawl. Buildings from the period 1977-1997 (yellow) are scattered around the city, and also forming several satellites on the north of the city. Buildings built since 1998 (blue) are forming extensions of the city sprawl in the north and especially in the south of the city, as well as expansions of satellites on the west and north of the city. Despite missing data were populated in this study, it is believed that it is better to present the missing data instead of the assumptions used for their construction periods.

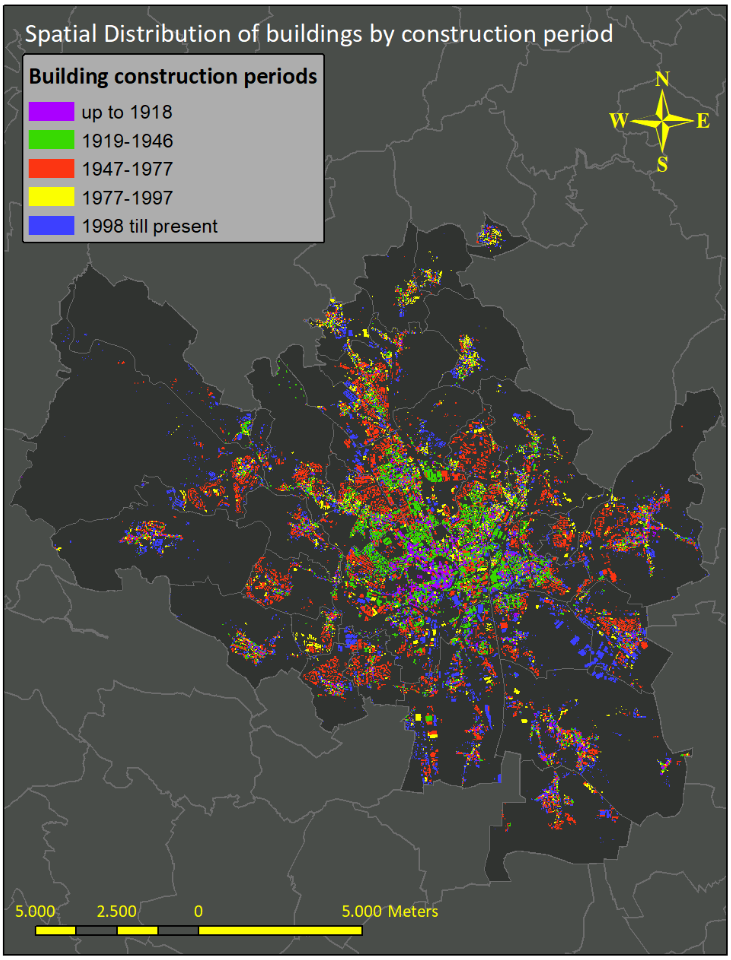
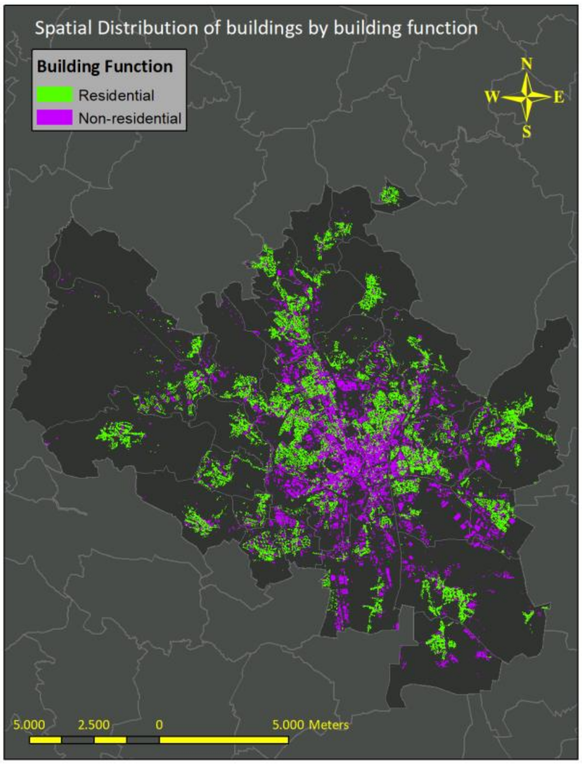


Figure 4.5 Spatial distribution of building construction period

4.2.2 Spatial distribution of buildings by building function

Following map in figure 4.6 shows the spatial distribution of buildings by building. One can see from the map, that the non-residential buildings are mainly present in the centre of the city and sprawling radially from the centre. Opposed to that are the residential buildings which are encirceling the city centre.

After assigning either residential or non-residential function to a building object, the total count of residential buildings is 64.698, and non-residential 22.660. This would suggest that the residential buildings are dominating the stock of buildings. However, the reader must bear in mind that the function was assigned based on the major function of the first floor of the building. This also explains the phenomenon we discussed in the previous paragraph. Many buildings in the centre of the city have a commercial or other non-residential function on the first floor, and residential function from the second or higher floors. This assumption therefore leads to misleading interpretation of the functions and is addressed in the discussion section. On the contrary, buildings with residential function on the first floor are most likely to have a residential function also on other floors.



4.6 Spatial distribution of buildings by building function

4.2.3 Spatial distribution of absolute material stocks

In the following three maps, the absolute amounts of material stock in ton/100.000m^2 are displayed. These maps help to get an idea about the spatial distribution of total amounts, their quantities, and their locations.

All three maps in this section use the quantile classification, meaning that each category contains about the same number of elements. Before discussing the results, it is worth mentioning that the upper quantile (the top 20% of the values) for all three materials is higher by a full range of magnitude. This means that the top quantile contains about ten times more ton/100m^2 than the quantile below, which might lead to misinterpretation.

The following maps are annotated with numbers for areas of interest, which are referred to in the text. The size of the font was chosen small on purpose not to obfuscate the data highlights, therefore zooming in is recommended. Note: unit on the figures states ton/100m^2, however, the correct unit is ton/10.000m^2, as stated in the caption.

Concrete

In figure 4.7, the spatial distribution of the total amounts of concrete is displayed. The highest amounts of concrete are located in the *Brno-Město* (1) and its surrounding neighbourhoods *Zábrdovice* and *Černá Pole* (1a), *Staré Brno* (1b) and the district Žabovřesky (2). High amounts of concrete are also situated along a road leading north of the centre in the *Královo Pole* (3) district, which is a large residential area but also have its district centre and panel house estates. Several other locations also contain higher amounts of concrete. Namely, district *Bystrc* on the west (4), which has a large panel house housing estate, and a similar case is for the districts *Starý Lískovec*, *Nový Lískovec* and *Bohunice* (5) on the southwest, and *Vinohrady* district on the east (6). Large residential area in the district *Řečkovice a Mokrá Hora* (7) also contain high amounts of concrete, similar to the district *Lesná* district (8). The *Slatina* district (9) on the southeast border on the border of the city has also panel house estates but serves also as an industrial area, with a nearby airport. Finally, the *Brno-South* district, namely the municipality *Dolní Heršpice* (10), on the southern border of the city, is a significant industrial and commercial area with high accumulations of concrete.

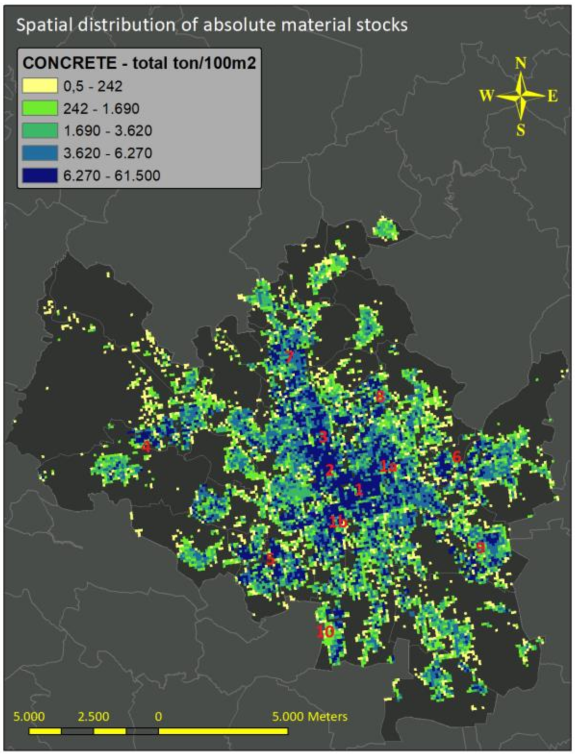


Figure 4.7 Concrete – total material stock (ton/10.000m^2)

Bricks

In figure 4.8, the spatial distribution of the total amounts of bricks is displayed. As for bricks, we can see a similar story as for concrete as described in the previous section. The differences are that the centre and the extended centre have by far the highest accumulations of concrete. Namely districts *Brno-Město* (1), *Žabovřesky* (2), *Staré Brno* (3), *Zábrdovice* (4), *Černá Pole* (5), and *Královo Pole* (6). The other districts described previously (7) still have higher accumulations of bricks than other areas, but slightly less relatively compared to concrete, since the panel estates in these districts do not use as many bricks, however, there are also residential areas with regular brick houses. One exception is the *South-Brno (8)* district, which does not show any major accumulation of bricks as compared to concrete, probably due to its industrial and commercial character. Another interesting observation is that parts of the districts *Židenice* and *Černovice* (9) show a relatively higher accumulation of bricks as compared to concrete, most probably due the old construction period of the neighbourhood, for which bricks were typical.

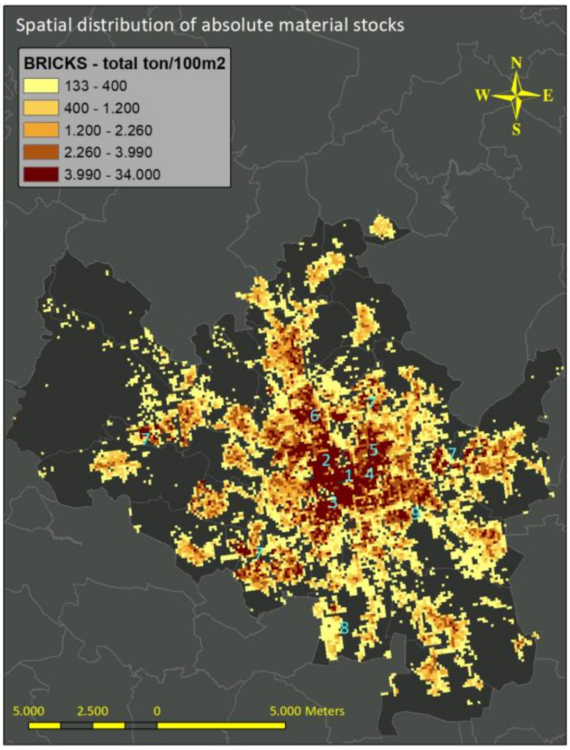


Figure 4.8 Bricks – total material stock (ton/10.000m²)

Mortar

In figure 4.9, the spatial distribution of the total amounts of mortar is displayed. In the case of mortar, it is practically the same situation as with bricks. These two materials are often used together; therefore, this result is an expectable one.

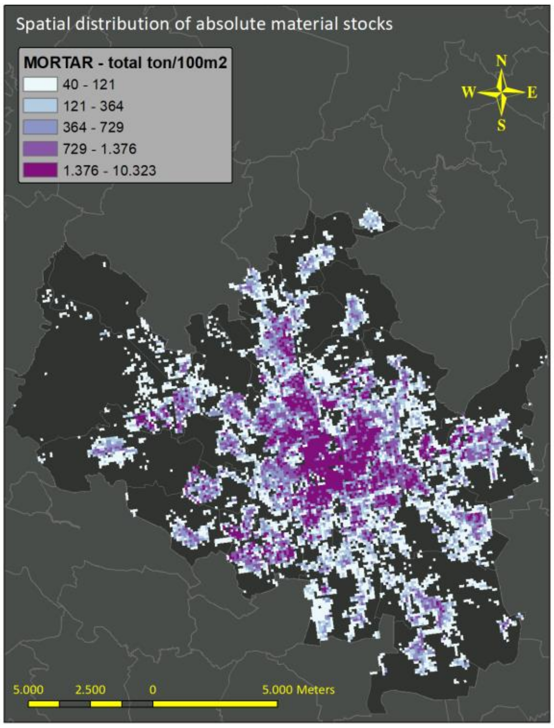


Figure 4.9 Mortar – total material stock (ton/10.000m²)

5. Chapter: Discussion

In this chapter, the results and implications are discussed along with reflections and scientific contribution.

5.1 Results Discussion and implications

In this section, the results found in this study and what they mean for this research are discussed.

5.1.1 Material stock in the context of the city

Brno is a city with a historical centre in the heart of the city, in the *Brno-Střed* district (*Brno-Centre* district) which grew up until the year 1918. Buildings from this period are the least numerous among the other periods and their total material stock is the lowest. Buildings that originate from this period represent historical buildings, especially because they also include buildings from before the 20th century, and it can be assumed that most of these buildings will be preserved, therefore, not available for urban mining.

Between 1919-1946, the extended centre developed towards the north of the city centre in districts like *Žabovřesky, Královo Pole, Brno-Sever, Židenice,* and *Černovice*. Buildings from this period are the second most numerous and the total material stock is also the second highest among the other periods. It can be assumed that part of these buildings will be also preserved for their historical value, but a part of them are buildings at the end of their use phase, and potentially available as an urban mine in the near future.

During the 1947-1977 period, the buildings with the most numerous representation and with the largest material stock were built, especially panel house estates in districts such as *Starý* and *Nový Lískovec, Bohunice, Kohoutovice, Bystrc, Komín, Slatina, Líšeň,* and *Vinohrady,* and in the municipalities *Řečkovice* and *Lesná.* Additionally, already existing districts such as *Žabovřesky* and *Královo Pole* were also expanded with panel house estates. Since many of these districts demonstrated the highest accumulations and concentrations of especially concrete, they would make a prospective material stock for urban mining. The functional lifespan of panel houses was expected to be about 30 years, however, in reality, they proved that they can last up to 100 years, depending on their maintenance and renovation (Kokas et al., 2020). Therefore, buildings that were built earlier in this period and those in worse condition could represent a potential urban mine.

Buildings from the 1977-1997 period are generally scattered around the city, most probably replacing previously demolished buildings, they can be found mainly in satellite districts *Ivanovice, Jehnice, Ořešín, Útěchov,* and in the municipality *Soběšice* of the *Brno-Sever* district. Additionally, several large commercial buildings can be found in the *Brno-Jih* district. This cohort of buildings represents both the second least numerous and second smallest material stock. Since these buildings were built relatively recently, it cannot be expected they would be available for urban mining in the near future.

The cohort of buildings from 1998 till today represents both the third most numerous and the third biggest material stock. Similar to the previous time period, buildings from this cohort are rather scattered around the city, but they also represent significant expansions of several districts, such as the university campus in *Bohunice* or other districts such as *Žebětín, Bystrc, Medlánky, Královo Pole, Ivanovice,* or *Soběšice*. Additionally, they account for a large development in the *Brno-Jih*, Černovice, *Slatina, and Tuřany* in the south and southeast of the city, where large industrial and commercial areas are located. Buildings of this cohort are built most recently, hence, they cannot be considered for urban mining in both short- and mid-term.

The conclusion here is that buildings especially from the period 1919-1946 and partially buildings from the period 1947-1977 represent the best potential for urban mining. Implications of these findings are that we can now estimate roughly the amounts of materials that will be available for reuse and recycling, which can help with scaling up or establishing waste processing facilities that would be able to handle the said amounts. Knowing, where the hotspots of these material stocks are, can be instrumental in deciding on the location of the facilities, which would be ideal as close to these hotspots as possible. On the other hand, it is also important to raise questions like whether there will be a future demand for end-of-life concrete, brick, and mortar materials. Additionally, whether the relevant stakeholders can promote and pursue future building design that counts on the reuse and application of recycled materials.

The total estimated stock of the two most promising cohorts – 1919-1946 and 1947-1977 – are shown in table 5.1 below.

Table 5.1 Material stock of builds from cohorts 1919-1946 and 1947-1977

	1919-1946	1947-1977
Concrete (t)	5.725.836	14.335.884
Bricks (t)	5.412.891	5.646.339
Mortar (t)	1.963.913	2.002.239

5.1.2 Results per capita

Many researchers study the material stock per capita, which can help to understand many factors such as the space use efficiency, population density, relationship between the height of building and materials used. The material stock per capita in this research are shown in the table 5.2 below, along with values per capita for the inner-city centre (Brno-Město cadaster area), which population was 5300 in 2021 (Český statistický úřad, 2022). The calculations are discussed in Annex 12.

Table 5.2 Total mass and mass per capita (per material and sum)

	Total mass (t)	Mass per capita (t/c)	Mass per capita Brno-City (t/c)
Concrete	34.464.129	89	146
Bricks	16.272.617	42	189
Mortar	5.648.915	15	59
SUM	56.385.661	146	393

The total mass per capita in this case is 146 ton per capita, which corresponds with the results found in other studies. For instance, a study conducted in Salford in 2004 resulted in 111 ton per capita, study in Wakayama in 2004 resulted in 247 ton per capita, a study in Padua in 2007 resulted in 209 ton per capita, and study in Vienna in 2013 resulted in 210 ton per capita and at 149 ton per capita in 2018 (Miatto et al., 2019). The value of this thesis shows a somewhat lower value per capita, as compared to the abovementioned studies, however, this study only covered three materials, while other studies also included steel, timber, glass and other materials. Therefore, this is a validation that the results of this study are comparable to other studies, however, one must bear in mind that the material intensities used in this study could contribute to the comparability of the results between these studies, not necessarily that Brno has a similar character as the other case studies.

There are studies that yield significantly different per capita values because they only assess city centres/downtowns, which are generally more concentrated in material stocks. This is also the case for Brno, where material stock in Brno-Město (Brno city centre) is about 393 tons per capita. However, using a comparison for instance with a study of Wakayama, Japan, (Tanikawa & Hashimoto, 2009) with population density in the city centre similar to Brno; it is a study that yields significantly higher material stock in the city centre, the material stock in residential buildings was 108 ton per capita. While for the case of Brno, it is only 29 tons per capita in residential buildings in the city centre. This inconsistency was already pointed out in section 4.5.2, where we discussed that many buildings were probably misallocated to a non-residential function, resulting in such extreme lows in material stock per capita in residential buildings. This can be also confirmed in the following figure 5.1, which zooms in on the city centre. One can see that most of the buildings in the city centre, in the red circle, are allocated as non-residential, while realistically many of these buildings serve for significant amount of residential function.

5 Zoom in on city centre

On the contrary, there are also case studies, such as a study on Taipei (Cheng et al., 2018), that yield significantly lower per capita values because they investigate densely populated cities (Miatto et al., 2019), however, this is not the case of Brno.

5.2 Research Limitations

This section discusses the assumptions made in this research and their associated limitation.

5.2.1 Research scope limitations

The general limitation of this study is the fact that it's conducted only for one moment in time, looking only at the currently existing buildings. This research boundary does not undermine the results of this research, however, it poses limits to the translation of the results into more for instance prediction models for the outflows of demolition materials. The second general limitation is that the scope of this research only covers three structural materials – concrete, bricks and mortar. This again does not undermine the results of this study, though, it does not provide a more complete picture of what is contained in the building material stock and limits the ability to compare with other case studies. Nevertheless, the three chosen materials were the three most numerous materials found in buildings in general.

Next, the study does not consider basements and roofs of different volumetric shapes, meaning that material stock is only calculated for structures above the ground and roofs are considered flat in this model. This poses a significant limitation to the study in terms of mapping the total material, as the basement and roof account for about 30% of the total building volume, as estimated by Kleeman et al. (2017).

5.2.2 Building function assumptions

Another limitation is that building functions are not too differentiated, as only residential and non-residential buildings were considered. The residential buildings could be stratified into small, medium and large residential buildings, similarly to how Miatto et al. (2019) did in their Padua case study. The non-residential buildings were even more aggregated here since many different types of buildings were put in this category, except strictly atypical structures, as discussed in the Method chapter (section Data Processing). Other studies differentiate also into building functions such as industrial and commercial, which is useful for more recent buildings using more metals for construction, such as warehouses, or malls. Nevertheless, the ability to differentiate buildings by their function is conditioned by available data for material intensities, which in the case of this study only allowed for residential and non-residential functions. Furthermore, when determining the function of a building, the function of the first floor was taken as the leading function. The dataset used in this study provides building function information for up to 18 floors of the building, and even the percentage of the function on the first and second floor. The choice for using the first floor's function as the selected function was an assumption to simplify the process, however, as we have seen when discussing results per capita, this has led to a very one-sided allocation of buildings towards non-residential buildings in the city centre. The implication of the choices for building functions might lead to misleading results in terms of assigning the incorrect function to a building, resulting in assignment of an incorrect material intensity value.

5.2.3 Material intensity data assumptions

As for the material intensities itself, an important modelling choice made in this study was choosing a substitute data from a Vienna study (Kleemann et al., 2017). Despite trying to choose the best fit to substitute the missing material intensity data for Brno, this assumption carries significant implications. Vienna and Brno are historically and administratively intertwined, therefore, a relative similarity can be assumed, however, both countries developed more independently since the end of the first world war, potentially meaning that the technical aspects and material compositions of buildings could differ. Additionally, the material intensity dataset of Vienna has its own limitations:

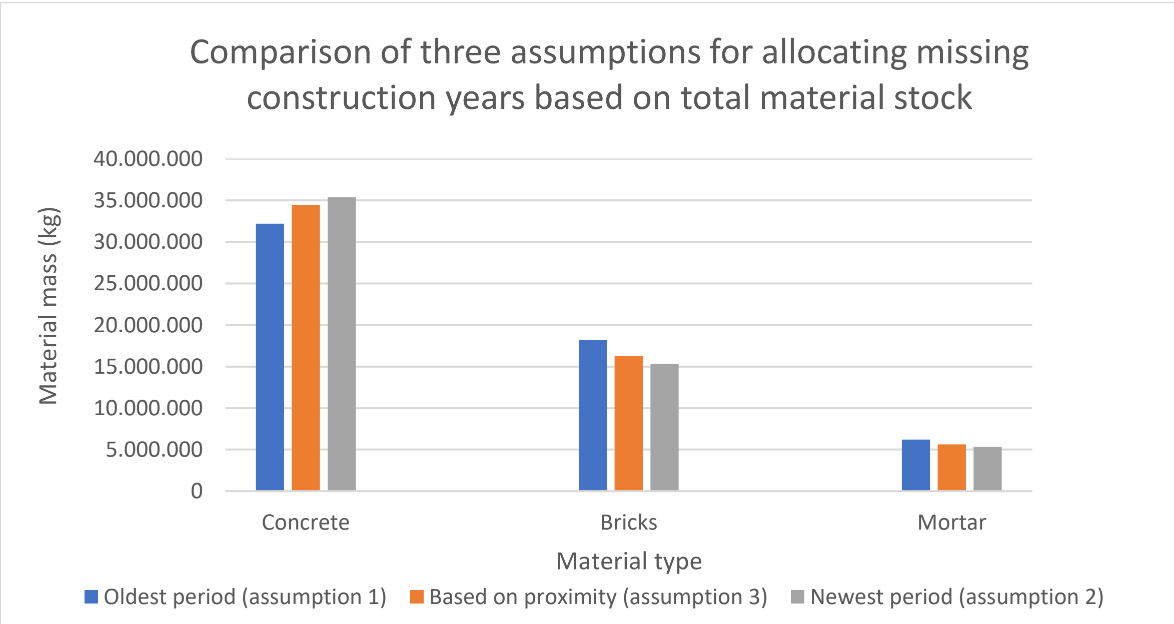
- Material intensity for bricks in residential buildings in period 5 based on only 2 data inputs, which values were averaged
- Material intensity for all materials in non-residential in period 3 had no data, therefore, they were based on an estimation
- Material intensity for all materials in non-residential in period 4 based only on 1 data input, and in period 5 based only on 2 data inputs, which were averaged

This is discussed more in detail in the Method chapter (section Material intensity table), where source and calculations are referenced to.

The reader should bear in mind that using an alternative dataset for material intensities leads to systematic inaccuracy of the material stock results. This might be observed for instance in a different ratio of used materials when comparing buildings from the same period, same surface area and number of floors. For example, a building in Vienna could contain relatively more bricks and less mortar as compared to a building in Brno or use different materials altogether. Secondly, buildings with the same number of floors might have different heights and volumes, resulting in different building material stocks. On the other hand, it is safe to assume that there are technical limitations to substitute materials or deviate from a ratio of for instance brick to mortar use. Also, due to the similarity and history of these two cities, it can be expected that building standards would not differ significantly when considering for instance floor heights or wall thickness. More careful interpretation of the results may apply to buildings from the second half of the 20th century and further due to different political development and administrative disconnection of these cities. However, it can be assumed that the results would not differ in an order of magnitude and could serve well for high-level planning due to the arguments above.

5.2.4 Missing construction period data

Finally, the construction period of about 20.000 buildings (25% of the dataset) had no value, therefore, three different assumptions were tested to populate the missing data as explained in the Method chapter (section Missing construction period data). The total material results for each of the assumptions were generated and compared, to see how much they deviate from each other, as can be seen in figure 5.2 below.



5.2 Comparison of three assumptions for allocating missing construction years based on total material stock

The results of the third assumption always fell between the results for the other two assumptions (which represent the most extreme results), meaning the third assumption represents the most suitable assumption for assigning the construction period values. Using an assumption for allocating the construction period value to 25% of the dataset clearly poses some uncertainty about its accuracy. For that sake, table 5.3 was created to demonstrate the effect of the assumptions on results in terms of how much the results of assumptions 2 and 3 deviate from results using assumption 1. From the table, we can see that assumption 2 never deviates more than 10% from assumptions 1 and 2, meaning the maximal error in accuracy can be 10%.

Table 5.3 Effect on total results based on different assumptions (as compared to assumption 1)

	Concrete	Bricks	Mortar
Oldest period (assumption 1)	100%	100%	100%
Based on proximity (assumption 3)	107%	90%	91%
Newest period (assumption 2)	110%	84%	86%

Alternatives for the assumptions and ways to overcome some of the limitations are proposed in the Further research suggestions section of this chapter.

5.2.5 Data quality, availability, and collection

The data quality of the objects geodatabase with attributes is relatively high, since we used a dataset that was produced based on a three year project that already built upon previous research, combining several models and methods. This pertains namely to location of objects, building area, building functions, number of floors that the original dataset had. The quality of the construction year data was decent, as it broke down the time into 6 different periods in the original dataset, as can be seen in similar studies. Limitation was seen in about 25% of the objects having missing data for the construction period. All of these data were available in form of public data, except the construction period data, which were, however, easily obtained after communication with the Architect Office in Brno.

The main obstacle was posed by the unavailability of the material intensity data for Czech Republic or Brno. They were not found in public online literature and other sources, neither after contacting around 130 different relevant parties, which seems represents relatively exhaustive search. This led to use of alternative material intensity from the Vienna study, which data were readily available. This dataset had its own limitations as discussed in previous section, however its quality is relatively high, as it has been compiled based on numerous case studies and technical documentations. Using an alternative material intensity data meant also that the attribute data of the original dataset had to be matched to this alternative material intensity data categories (transforming construction periods), which reduces the potential of the original dataset, which is of relatively high quality. There is a chance that material intensity data would be available searching physical sources in local libraries and other documentations in Czech Republic, however, it would be also expectable that respected figures and institutions would be aware of the existence of these data, which was not the case.

5.3 Reflections

Reflecting on the method used in this search, allocation of functions to buildings could have been handled better. In the case of this study, many buildings that bourne also largely residential functions were written off as non-residential. Perhaps a better approach would have been assigning the leading function based on the function that is on majority of floors instead of the function of the first floor. Additionally, allocation of missing construction period data could have used more sophisticated assumptions, however as was demonstrated, the inaccuracy was limited to maximally 10%, therefore, it is not the biggest set back of this study.

Furthermore, this study would have benefited from more in-depth analysis of the circular C&D industry. This study was only limited to gaining a general overview of the industry, its characteristics, actors, challenges and trends, however, no real analysis of literature in this sense was conducted. Analysing the policy relevance aspects would have produced more informed recommendations, and could also tell something about the how the circular C&D should work better towards improvements, rather than advising recommendations based on the GIS results.

Reflecting on the results of this study, more in-depth insights could be gained by studying the city more on a neighbourhood basis. This could be in form of creating specific invetory of different neighbourhoods with their material stocks and age. As for the policy recommendations, they are limited only to leveraging insights gained from the GIS analysis and use policy aspects more as an orientation on how to leverage these insights, instead of bringing something new in terms of insights into the working of the governance and transition aspects of the circular C&D.

5.4 Scientific Contribution

The contribution of this study lies in the investigation of the urban mine, namely the second step – exploration – of the urban mines, which establishes more detailed stock characterization and provides insights into the grade, size of stock and related uncertainties. These can be further evaluated for the selection of suitable technologies for their extraction and for further economic analysis of their costs and revenues, which represents the third step of anthropogenic stock evaluation.

This study contributes to the existing inventory of case studies investigating material stocks using the same or similar approach, which allows for greater understanding and enables comparison of structural differences of urban mines across the world. Once data for Brno or Czech Republic are available, it can also be observed to what extent using an alternative material intensity dataset had an impact on the actual results.

In terms of methods used, this study tested three different assumptions for allocating missing data of construction periods. Though, these might not be the most elegant solutions to missing construction period data, they are a relatively quick way to allocate these data and also mark what are the maximal possible errors using these assumptions, when all objects with missing data are either allocated to the oldest or the most recent period.

In terms of contribution to the policy aspects of this study, despite this study not performing any analysis to this discipline, it identifies the relevance of GIS for both where and how are its results used, and whom are they most relevant to.

6. Chapter: Conclusions and Recommendations

Finally, the recommendations for C&D industry actors are given, research questions are answered, the key takeaways summarized and further research is suggested.

6.1 Recommendations

This section puts the results in the context of circularity in the C&D, and their implications are illustrated in the form of policy recommendations. The results of the GIS analysis are translated into recommendations using the insights from Chapter 2, section 2.2 and Chapter 5, section 5.1, namely how can such GIS analysis be used in C&D circularity, followed by recommendations for relevant stakeholders.

6.1.1 GIS use for policymaking

This section is a general recommendation for any actor interested in urban mining and how can GIS the process of improving the circularity of C&D, using examples from this case study.

GIS data analysis can be used for **systematic data collection in a structural way**. This will help establishing a baseline on various issues, which is a departing point for better, data-driven decision making. In this study, it was shown how data were collected, evaluated, combined and used to inform further steps.

Once data are collected, government agencies and other interested subjects can **identify, characterize and quantify material stocks**. Such analysis pertains to answering questions such as what are the amounts of materials present in our society, how old are the stocks, and where they are concentrated. This has been shown in the results section of this study.

The obtained results can be used in various ways. One of the most relevant applications is **planning for reuse or recycling of the waste materials**. The results provide information about what the rough quantities of materials will be, then appropriate measures can be taken in terms of what equipment for sorting/processing of waste materials should be used on-site and what is beyond processing on-site and needs to be processed in a remote facility.

Next, it can help to determine the **locations of the waste treatment and sorting facilities**, because the long distance between the demolition site, sorting and treatment facilities makes recycling of materials, especially bulk ones like concrete, uneconomical (Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, 2018). Finally, it can be used to establish what **capacity of waste treatment facilities** will be required to handle future demolition outflows. GIS data combined with MFA can model and predict future demolition outflows, which can be then used to anticipate the supply of waste material and plan the waste treatment capacity accordingly.

6.1.2 Municipality

This advice is relevant for local municipalities and other authorities involved in C&D on a municipal level.

Municipalities need to understand the urban metabolism of their city. That means gaining insight into existing material stocks, their location and quantities. Factors such as geographical location of major material hotspots and their temporal character (when will they become available), location of sorting and waste treatment facilities and their capacities, population density and transportation costs should be well understood. Results of this study identified locations of future material hotspots and their maximal potential material stocks. Expanding on these results can be used to predict future material flows. These findings play an important role in planning and decision making for new waste sorting, treating and processing facilities and their capacities.

Municipalities should also be in charge of collecting the data in a systematic way, since it would be hard to do this on the national level. Municipalities should be in charge to ensure consistency, and make the data and results available for the public, as well as updating these information over time. This also means collecting information about the inflows and outflows of the C&D projects. Especially larger municipalities should make use of reuse and recycling, because in the bigger cities, there is a better and more developed market for recycled and reused products. They should foster the trade of these materials, which will further develop the market and improve the quantity and price competitiveness of the market.

Finally, municipalities should promote and participate in pilot projects for circular construction and demolition, which integrates actors from across the whole C&D supply chain already from the design phase. This way, the problematic of material recycling can be better understood and necessary measures can be taken for large projects.

Recommendations

Specific recommendations for the municipality is given per areas of interest in table 6.1.

Table 6.1 Municipality recommendations

Area of interest	Actions
Evaluate more in depth the potential material stock from 1919-1946 and 1947-1977	Study expected survivability and volumes of material outflows of materials of these material stocks. Conduct study on other materials contained in this stock.
Evaluate C&D waste processing capacities	Establish communication with demolition, waste sorting, treatment and processing companies Analyse capacity, inventory of recycled materials, current recycling rates, supply-demand of secondary C&D resources Locate major material stock hotspots and current recycling facilities. Determine how future material outflows can be handled based on capacities of present and future recycling facilities. Aim for short distances from demolition site to facility. Following national regulations, set goals and actions to meet the future material outflows
Set up systematic data collection in both construction and demolition	Track material inflows during construction, and outflows from demolition sites. Monitor recycling rates, recycling capacities, trade of secondary C&D resources.
Assist local demolition, waste sorting, treatment and processing companies in improving the circularity of C&D projects	Identify and target local barriers to increasing recycling and reusing in discussion with relevant actors Promote and participate in pilot projects for circular construction and demolition Facilitate local/regional market for secondary materials. Connect relevant actors and expand customer base of secondary material platforms

6.1.3 Government

This advice is relevant for ministries, such as the Ministry of Environment, Ministry of Industry and Trade, and Ministry of Regional Development.

As based on literature and other sources reviewed in Chapter 2, governments should create an ideal environment for circular C&D by incentivizing the use of reused and recycled materials by:

- Increasing fee for waste deposit
- Subsidizing or otherwise supporting the adaption of innovative business models
- Spreading awareness and sharing knowledge among different actors
- Create suitable regulations that guide more circular practices, reward those who participate, and penalize those who do not comply
- Integrate vertically across different authorities that stipulate regulations and laws, so that responsibilities are clearly defined, regulations are transparent and guiding, and not contradicting each other
- Support R&D and foster collaborations among different fields studying the built environment, buildings, and C&D

Recommendations in the context of the current framework for circularity

The Action Plan of the Strategic Framework for Circular Economy of Czech Republic 2040 (Ministerstvo Životního Prostředí, 2022b) sets out three overall goals that are related to the circular C&D:

1. Optimal use of materials
2. Increase the use of secondary materials
3. Use primary materials only when needed

Goals 1 and 2 can be supported by using the insights of this study from Chapter 2 and 5 as shown in table 6.2.

Table 6.2 Government recommendations

Framework goal	Area of Interest	Actions
Optimal use of materials	Promotion of systematic data collection	Stipulate or incentivize municipalities to collect relevant GIS data on a municipal level as used in this study. Currently municipalities only collect these data voluntarily. Conduct or assign several case studies to collect data about material intensities for various functions and construction period of buildings in Czech Republic.
	Management of available materials and tracking their flows	Support municipalities in expanding the market of secondary materials by providing trade data, instruments, regulations and platforms to incentivize the trade
Increase the use of secondary materials	Planning for recycling facility capacity by predicting quantities and types of materials that will require waste treatment	Collaborate with municipalities to review and plan recycling capacities and future outflows Set targets for recycling and reuse of secondary materials
	Use the case of Brno as a pilot study	Collaborate closely with Brno to evaluate the outcomes of material stock studies and projects on urban mining before scaling them up nationally

Current actions on the Action plan 2022-2027 – 1) technical standard for pre-demolition audits for subsequent selective demolitions, 2) extended use of BIM in the private sector, 3) Level(s) framework implementation for public procurement – do address these goals, however, they are complimentary to the proposed recommendations above. The recommendations can be applied as additional actions to the existing actions or be implemented in the next Action plan 2028-2033.

6.1.4 C&D supply chain

This advice is relevant for demolition companies, waste sorting, treatment and processing companies but also the broader C&D supply chain.

In the C&D supply chain, different actors need to collaborate in order to improve circularity. Collaboration with developers, investors, material producers, designers, architects, contractors, facility managers, tenants, demolition companies, sorting and waste treatment companies, R&D and other relevant actors from the make-phase till the end-of-life phase will allow for more resilient and circular C&D. Increased use of tools such as BIM (building information modelling) will help to easily access the information about material composition of buildings and estimate demolition waste for all interested parties. The supply chain should come together to conduct pilot projects, that would demonstrate the technical, procedural and financial feasibility, and inspire more projects like this in the future.

Demolition companies can use the results of this study to project plan their future capacities based on the estimated material stocks and their quantity. Demolition companies can prepare for future challenges and meet them with the right equipment, procedures, and marketable services. Similarly, waste facilities can project their processing capacities and plan for expansions based on future materials outflows and locations of these hotspots.

All actors in this supply chain should explore innovative business models, employ novel technical solutions, and make use of governmental incentives for adapting circular practices. Participation in circular construction & demolition pilot projects can be a way to understand the challenges and trends in circular C&D and use it to gain domestic and international market advantage.

Collaboration of demolition and waste treatment facilities with municipal and governmental agencies can be mutually benefitting. These companies can help authorities understand the material flows, but also challenges and barriers in sorting and processing, which the authorities can address with suitable laws and market incentives.

Recommendations

Specific recommendations for demolition and waste processing companies are given in table 6.3.

Table 6.3 Recommendations for demolition companies and waste processors

Demolition companies	Provide reliable data about material outflows and other relevant information to municipality (e.g. types of material, sorting capacity and abilities, etc.) Collaborate with waste processors to improve waste processing (e.g. providing pre-sorting)
Waste sorting, treatment, and processing	Provide reliable data about waste material inflows and other relevant information to municipality (e.g. types of material, processing capacity and abilities, recycling rates, etc.) Project and plan future waste processing facilities and capacities to meet future waste material inflows
For all actors	Collaborate with municipality and other authorities to address existing challenges and barriers Participate in collaborative pilot projects on circular construction and demolition to gain better understanding and domestic/international market advantage Address challenges with innovative business models, employ novel technical solutions, and make use of governmental incentives for adapting circular practices

6.2 Answering the research questions

In this section, the research questions are answered:

1. What geographical data and attributes are available for buildings in Brno?

The data for building location, building surface area, number of floors, building functions and construction period are available. Data for the construction periods are missing in about 25% of objects. Material intensity data were not found for Czech Republic or Brno.

2. What approach has to be taken based on the existing data in order to generate the material stock of concrete, bricks and mortar of buildings in Brno?

The geographical approach is used for research design, while the main research method is the bottom-up GIS approach. Missing data for the construction periods are populated based on the most suitable assumption out of three assumptions. Missing Material intensity data are substituted with material intensity of a case study on Vienna, Austria. Data from the original dataset are harmonized to create classes based on a combination of construction year and function to match the Vienna dataset.

3. What is the spatial distribution and total material stock in buildings in Brno?

The material stock from the period up to 1918 is concentrated in the *Brno-Střed* district. Material stock from the period 1919-1946 is concentrated in and around the extended centre of the city, namely in districts *Brno-Střed, Žabovřesky, Královo Pole, Brno-Sever, Židenice,* and *Černovice.* The materials stock of the period 1947-1977 is concentrated especially in panel house estates in districts such as *Starý* and *Nový Lískovec, Bohunice, Kohoutovice, Bystrc, Komín, Slatina, Líšeň, Vinohrady, Řečkovice* and *Lesná*. The material stock from the period 1977-1997 is generally scattered around the city, often replacing previously demolished buildings; aside from that can be found mainly in satellite districts *Ivanovice, Jehnice, Ořešín, Útěchov,* and *Soběšice*. The material stock from the period 1998 up to now is generally scattered around the city, but also represents significant expansions of several districts, such as the university campus in *Bohunice* or other districts such as *Žebětín, Bystrc, Medlánky, Královo Pole, Ivanovice,* or *Soběšice*. Additionally, they account for a large development in the *Brno-Jih*, Černovice, *Slatina, and Tuřany.*

4. How can the material stock of buildings in Brno be characterized and interpreted based on the results?

The material stock of periods 1919-1946 and 1947-1977 represent the biggest potential for urban mining as this stock reaches its end-of-life phase. More than half of the material stock of buildings from the former period consists of bricks and mortar, while the latter contains concrete for about two thirds of the stock. The combined material stock potential from these two periods is 20.061.720 tons of concrete, 11.059.230 tons of bricks, and 3.966.152 tons of mortar.

The total mass per capita in the case of Brno is 146 ton per capita, which matches the results of other case studies focusing on developed countries, especially in the Western Europe.

5. How can the findings be translated into actionable recommendations for relevant stakeholders for improving the circularity of the C&D sector?

Results of GIS analysis can help government and other authorities, municipalities, demolition and waste processing companies to predict and prepare for future waste material outflows from the building stock. They can be translated to actions by advising each actor on their specific role in the process. Municipalities can conduct more in depth analyses of the material stock and future material outflows. They can help locate and organize waste processing facilities to plan for future outflows and capacities to meet the demand. They are also instrumental in monitoring progress, participating in pilot projects and helping local companies identify and target barriers for recycling and reuse.

Governments can enforce or incentivize systematic data collection, conduct case studies on material intensities of different building typology, assisting municipalities in expanding market for secondary materials, and set targets for recycling and reuse rates. Demolition and waste processing facilities can play instrumental role by providing reliable data about material flows, types of material, and their capacities. In turn, they can be better prepared for future waste material outflows and plan their capacities accordingly. These companies should meet the challenges of circular C&D by employment of innovative business models, novel technical solutions, make use of government incentives, participating in pilot projects to improve their domestic and international market position.

The main research question is answered below:

> *''How can be the knowledge of the current building material stock in the urban mine used to improve the building sector circularity of Brno, Czech Republic?''*

First of all, the results of the GIS analysis give an insight into the material stock, i.e. urban mine, of concrete, bricks and mortar, in terms of the characteristics of the material stock. This means – where are they located, at what quantities, where are the hotspots, what are the distributions of building functions and the age of the buildings. These insights help to navigate strategic planning, goal setting and decision-making. The results and insights are a piece in the puzzle of making the C&D industry (more) circular since changes have to take place on different levels – on the strategic, municipal, organizational, building level, and even on the level of construction products.

On the strategic level, policymakers and regulators should foster regulations that promote, especially financially incentivize, and enable circularity, while setting long-term goals and monitoring progress. Governmental agencies can use the results of this study and follow up steps, such as predicting future materials flows, as a case study for future scaling up of C&D circularity efforts. They can collaborate with municipalities on expanding the market of secondary materials, case studies on material intensities, which were missing in this study, set targets for recycling, reuse and enforce or incentivize systematic collection of data.

Municipalities must provide guidance in the process, collaborate with local actors, and enforce regulations, while planning and acting upon short- and mid-term goals. They need to take a leading role for connecting and organizing relevant actors in the region to collaborate, monitor and facilitate increase in recycling and reuse, meeting future waste material demands, and supporting the secondary resource market. They are also the ones who need to take the results of this study further to conduct more in depth analyses – project future outflows of waste materials, make more complete analyses (e.g. including roofs and basements, studying other materials).

Demolition and waste processing companies should seek out innovative business models that would take advantage of the financial incentives related to the transition towards circular economy and invest in innovative technologies, while participating in pilot projects to improve their market position domestically and internationally. They should provide municipalities with reliable data about the quantities and materials they process, while communicating their barriers and challenges for improving recycling and reuse in C&D.

The R&D institutions should support the development of both technical and social instruments. On the building level, construction projects need to employ a more integrated process that involves actors across the whole lifespan of the building early on in the process for a long-term perspective, while demolition projects should be addressed with better regulations on the separation of waste materials and enabling reuse and recycling of these materials to create secondary resources. On the level of construction products, materials and products should be designed and used with circularity in mind, so that buildings can be rather taken apart than demolished, including innovation around the business model and ownership of these products, such as extended producer responsibility or take-back systems.

6.3 Key Takeaways

In this section, key takeaways from this study are discussed:

- Results - material stock of buildings from periods 1919-1946 and 1947-1977 represent the biggest potential for urban mining, they together account for combined material stock of 20.061.720 tons of concrete, 11.059.230 tons of bricks, and 3.966.152 tons of mortar
- Government recommendations – create environment that fosters circular C&D with use of well-informed regulations, economical incentives, programmes for adaption of innovative business models, support of R&D and knowledge sharing, stipulate and incentivize municipalities to collect data, conduct case study on material intensities of building typologies in Czech Republic, support municipalities in goal setting and planning to waste treatment processes, and collaborate on pilot projects for future scaling up
- Municipalities – continue studying prospective materials stocks, predict flows and include other materials in the study, organize and facility communication among local and regional actors to understand current flows and capacities of demolition and waste processing facilities, support and facility secondary resource market, while assisting various actors from the whole C&D supply chain to enable circular C&D by identifying and targeting challenges and barriers by participating in pilot projects
- C&D companies – explore innovative business models, employ novel technical solutions, make use of governmental incentives for adapting circular practices, and carry out pilots in circular project, as a way to gain domestic and international market advantage, assist authorities with reliable data provision, plan for future waste material outflows in terms of capacity to meet the demand

6.4 Further research suggestions

Based on this research, and a review of other studies done in this field, further research is suggested in this section.

First logical suggestion would be to investigate other materials than those, which were covered in the study. This would mean other structural materials, but also non-structural materials, such as wood, copper or glass. These do not represent such high material stock as said concrete, bricks or mortar, however, they are often easier to remove from the building, they are replaced with higher frequency (and often still during the use-phase of the building), technologies exist that allow for easier and cheaper reuse or recycling of these materials, and therefore represent a low hanging fruit in terms of making the life cycle of these materials more circular.

Since this study focuses only on a snapshot of the current material stock, it would be useful to conduct a longitudinal study that investigates the material stock across different time periods. This will be helpful in predicting the material survivability and demolition outflows, which are key to waste management planning, in terms of establishment, location and capacity of waste processing facilities, similar to the studies performed by other researchers such as Miatto et al. (2019). Speaking about material outflows, further research can be conducted using the results of this study to predict the outflows utilizing existing data about demolition outflows either based on data from local demolition and waste processing companies or based on other case studies conducted elsewhere.

The next suggestion concerns material intensities since the data for this study had to be taken from another case, meaning the material intensities in this study may not be very accurate. The suggestion would be to conduct several case studies on individual buildings in their end-of-life phase to quantify the materials used in the building. Alternatively, investigating documentation about existing buildings, such as construction plans, bills of materials or procurement information of these buildings. This study is limited only to residential and non-residential buildings, therefore, further research could include also other building function types. This would be especially valuable if local material intensity data would be established, as proposed in the previous suggestion. Additionally, this study covered many buildings with missing construction year (about 25% of the total dataset), hence, the collection of information about the construction year of these buildings would complete the picture. However, as discussed in the Research Assumptions and Limitations section of this chapter, this might not be the priority. Finally, this study omitted the building volumes of rooftops and basements, therefore, a more complex study could provide more complete material stocks.

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Appendices

Annex 1: Literature review for material intensity data

The material intensity data for Czech Republic or Brno were not found. Please, see accompanying Excel sheet 'MS_Brno.xlsx', for the overview of sources that were reviewed in the process of searching for the material intensity data. In the tab 'KeyWords – Material Intensity', one can see the keywords that were used to search for the data, and results of this search, however, none of the results lead to discovery of the material intensity data. In the tab 'Contact list', one can see the list of people, organizations, institutions, and companies that were contacted in search for the material intensity data. Several contacts gave suggestions about whom to contact, which are also included in the list and were also contacted, however, none of these resulted in finding the material intensity data.

Annex 2: Construction period transformation

Since the categories of construction period needed to match the categories of the material intensity of the substitute dataset based on the Vienna study (Kleemann et al., 2017), the construction period categories of the original dataset had to be transformed to the construction period categories of the Vienna dataset. Please, see accompanying Excel sheet 'MS_Brno.xlsx', tab 'Construction period transform.'

Annex 3: Material Intensity table calculations

The material intensity data had to be substituted with a dataset based on the Vienna study (Kleemann et al., 2017). Please, see accompanying Excel sheet 'MS_Brno.xlsx', tab 'Material Intensity' for overview of all the datasets, and how the final material intensity was calculated.

Annex 4: Python Script for adjustment of the building function attribute

```
def func_class(x):
 if x == 'bydleni':
  return 1
 elif x == 'garaz':
  return 3
 elif x == 'zahradky':
  return 3
 elif x == 'maloobchod':
  return 2
 elif x == 'rekreace':
  return 2
 elif x == 'sklad, distribuce, logistika':
  return 3
 elif x == 'kancelare':
  return 2
 elif x == 'jine specificke vyuziti':
  return 2
 elif x == 'sluzby spotrebitelske':
  return 2
 elif x == 'jine zarizeni technicke infrastruktury':
  return 2
 elif x == 'bydleni':
  return 1
 elif x == 'stravovani':
  return 2
 elif x == 'skola':
  return 2
 elif x == 'prumyslova vyroba':
  return 2
```

```
elif x == 'nerusici vyroba, montaze':
  return 2
elif x == 'garaz nerezidencni':
  return 3
elif x == 'bez vyuziti':
  return 2
elif x == 'univerzita':
  return 2
elif x == 'sportovni zarizeni':
  return 2
elif x == 'ubytovani':
  return 1
elif x == 'zemedelska a lesnicka vyroba':
  return 2
elif x == 'jine zarizeni dopravni infrastruktury':
  return 2
elif x == 'nemocnice, poliklinika':
  return 2
elif x == 'nevyuzivany komercni prostor':
  return 2
elif x == 'cirkevni stavba':
  return 3
elif x == 'zarizeni socialni pece':
  return 2
elif x == 'velkoobchod':
  return 2
elif x == 'veda, vyzkum':
  return 2
elif x == 'lekar':
  return 2
elif x == 'prujezd':
```

```
  return 3
elif x == 'urad':
  return 2
elif x == 'jine kulturni zarizeni':
  return 2
elif x == 'studentske ubytovani':
  return 1
elif x == 'jiny objekt verejne spravy':
  return 2
elif x == 'jine zdravotnicke zarizeni':
  return 2
elif x == 'zpracovani odpadu':
  return 2
elif x == 'viceucelova zarizeni pro kulturu a sport':
  return 2
elif x == 'policie':
  return 2
elif x == 'armada':
  return 2
elif x == 'cerpaci stanice PHM':
  return 3
elif x == 'pamatka, hrad, zamek':
  return 3
elif x == 'vozovna':
  return 2
elif x == 'vystavnictvi':
  return 2
elif x == 'zubar':
  return 2
elif x == 'hasici':
  return 2
```

```
 elif x == 'parkovaci dum':
  return 3
 elif x == 'muzeum':
  return 2
 elif x == 'pohrebnictvi':
  return 2
 elif x == 'posta':
  return 2
 elif x == 'divadlo':
  return 2
 elif x == 'zoo':
  return 2
 elif x == 'nadrazi, stanice':
  return 2
 elif x == 'galerie':
  return 2
 elif x == 'soud':
  return 2
 elif x == 'letiste':
  return 2
 elif x == 'vezenstvi':
  return 1
 elif x == 'kino':
  return 2
 elif x == 'velvyslanectvi':
  return 2
 else:
  return 0
```

Functional class =

```
func_class(!function!)
```

Annex 5: Python Script for adjustment of the construction period attribute

```
def period_cla(x):
 if x == '0':
  return 6
 elif x == '1':
  return 1
 elif x == '2':
  return 2
 elif x == '3':
  return 3
 elif x == '6':
  return 3
 elif x == '7':
  return 4
 elif x == '8':
  return 5
 elif x == '9':
  return 5
 elif x == '18':
  return 6
 elif x == '21':
  return 2
 elif x == '22':
  return 3
 elif x == '99':
  return 6
 else:
  return 0
```

Functional class =

period_cla('!obdobi_1!')

Annex 6: Python Script for populating missing construction period data

Allocation of construction period (allocation of missing data to the period 1900-1918)

```
def periodT1(x):
 if x == '6':
  return 1
 elif x == '1':
  return 1
 elif x == '2':
  return 2
 elif x == '3':
  return 3
 elif x == '4':
  return 4
 elif x == '5':
  return 5
 else:
  return 0
```

Functional class =

periodT1('!period_cla!')

Allocation of construction period (allocation of missing data to the period 1998-present)

```
def periodT2(x):
 if x == '6':
  return 5
```

```
  elif x == '1':
    return 1
  elif x == '2':
    return 2
  elif x == '3':
    return 3
  elif x == '4':
    return 4
  elif x == '5':
    return 5
  else:
    return 0
---
Functional class =
periodT2('!period_cla!')
```

Allocation of construction period (allocation of missing data based on proximity)

```
def cy_1(x,y):
  if x != 6:
    return x
  elif y == 1:
    return 1
  elif y == 2:
    return 2
  elif y == 3:
    return 3
  elif y == 4:
    return 4
  elif y == 5:
    return 5
  else:
```

```
    return 6

cy_1(!join_1.period_cla!, !found_1r.period_cla_1!)
```

Annex 7: Python Script for assigning material intensity values

Classification function and year (Concrete)

```
def C3_MI(x,y):
 if x == 1 and y == 1:
  return 134.6
 elif x == 1 and y == 2:
  return 455.2
 elif x == 1 and y == 3:
  return 748.8
 elif x == 1 and y == 4:
  return 827.9
 elif x == 1 and y == 5:
  return 1138.7
 elif x == 2 and y == 1:
  return 170.6
 elif x == 2 and y == 2:
  return 786.8
 elif x == 2 and y == 3:
  return 1276.7
 elif x == 2 and y == 4:
  return 1390
 elif x == 2 and y == 5:
  return 1299.1
 else:
  return 0
---
Functional class =
C3_MI(!func_class!, !periodT3!)
```

Classification function and year (Bricks)

```
def B3_MI(x,y):
 if x == 1 and y == 1:
  return 925.4
 elif x == 1 and y == 2:
  return 542.4
 elif x == 1 and y == 3:
  return 426.3
 elif x == 1 and y == 4:
  return 533.8
 elif x == 1 and y == 5:
  return 119.6
 elif x == 2 and y == 1:
  return 1098.9
 elif x == 2 and y == 2:
  return 636.3
 elif x == 2 and y == 3:
  return 258.1
 elif x == 2 and y == 4:
  return 20.2
 elif x == 2 and y == 5:
  return 22.2
 else:
  return 0
---
Functional class =
B3_MI(!func_class!, !periodT3!)
```

Classification function and year (Mortar)

```
def M3_MI(x,y):
  if x == 1 and y == 1:
    return 301.8
  elif x == 1 and y == 2:
    return 217.4
  elif x == 1 and y == 3:
    return 158
  elif x == 1 and y == 4:
    return 177.9
  elif x == 1 and y == 5:
    return 13.5
  elif x == 2 and y == 1:
    return 323.9
  elif x == 2 and y == 2:
    return 211.1
  elif x == 2 and y == 3:
    return 78.8
  elif x == 2 and y == 4:
    return 4.7
  elif x == 2 and y == 5:
    return 35.6
  else:
    return 0
---
Functional class =
M3_MI(!func_class!, !periodT3!)
```

Annex 8: Visual Basic Script for calculation of material stocks per object

Material intensity of given material intensity value * shape area * # of floors

Material stock of concrete

[C3_MI] * [Calc_Area] * [npodl]

Material stock of bricks

[B3_MI] * [Calc_Area] * [npodl]

Material stock of mortar

[M3_MI] * [Calc_Area] * [npodl]

Annex 9: Visual Basic for calculation of material stocks of object, ton/m^2

Material stock of concrete t/m^2

[C3_AM] / [Calc_Area] * 1000

Material stock of bricks t/m^2

[B3_AM] / [Calc_Area] * 1000

Material stock of mortar t/m^2

[B3_AM] / [Calc_Area] * 1000

Annex 10: Results

The graphs were constructed based on the final dataset and set of calculations, which can be seen in the accompanying Excel sheet 'MS_Brno.xlsx', tab 'Results'.

Annex 11: Spatial distribution of buildings by construction period with missing data

In figure B below, one can see the spatial distribution of buildings by construction period; this map includes data with missing construction period data as compared to the map in the Result chapter, where the missing data were populated based on assumption.

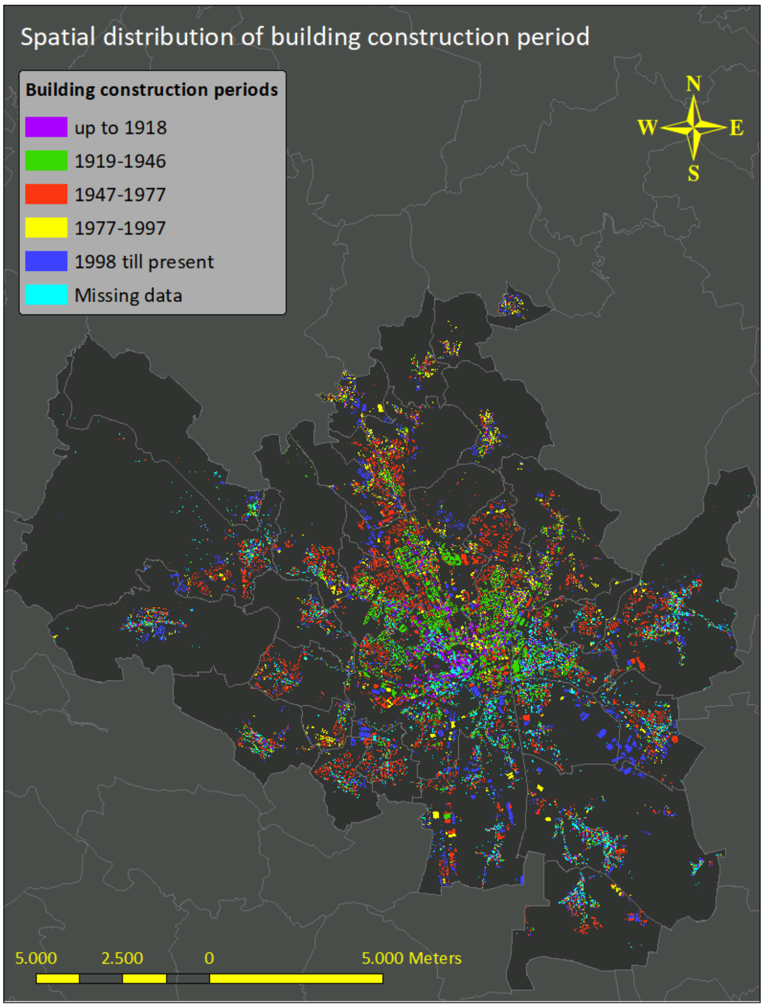

Figure B Spatial Distribution of buildings by construction period (with missing data)

Annex 12: Material stock per capita

The material stock per capita was constructed based on the final dataset and set of calculations, which can be seen in the accompanying Excel sheet 'MS_Brno.xlsx', tab 'Results'