# The Missing Stock: Exploring Concrete Use in Trondheim's Residential Building Foundations

(Newly built residential houses in the Tiller-Hårstad neighborhood, image made by the author)


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# Abstract

Concrete is one of the most widely used materials in residential building construction. It contributes about 4% to 7% of global greenhouse gas emissions annually. Thus, better understanding the material stocks and flows of concrete can support efforts to better manage this resource and its use. Concrete is especially popular for the construction of building foundations. Previous research has shown that foundations can account for 25% to 60% of residential housing mass. Despite this, no in-depth analysis of material requirements of foundations has been conducted. Foundation design depends on the housing type and soil type. Considering foundations' substantial share of building mass, I analyze them in this thesis in the form of a case study of residential housing built in Trondheim between 2010 and 2020. To account for all emissions from cradle-to-construction site I also compare the concrete production emissions to the last-leg transport emissions. The residential building foundations' material requirements were estimated with a model I specifically developed for this thesis. 507 000 tonnes of concrete were used from 2010 to 2020 to build residential building foundations in Trondheim. The results show that the concrete production emissions represent 99% and the last-leg transport emissions 1% of the total cradle-to-construction site emissions. The average material intensity coefficient across all buildings in Trondheim is 402 kg of concrete in the foundation per one $m^2$ useful floor area. I disaggregated the buildings into five types: single family house, semi-detached house, rowhouse, apartment building, assisted & communal living. When disaggregated, the building types' material intensities vary, on average, 8% around 402 kg/$m^2$ useful floor area. The largest difference being 20% below the mean. As a result, there are no substantial differences of material requirements per $m^2$ useful floor area between different building types. However, building on peat and bog soils increases the material requirements by 80% compared to all other soil types found in Trondheim. This is due to the low bearing capacity of peat and bog soils. Trondheim currently plans its residential zoning until 2034. 5% of the planned zones are located on peat and bog. A rough estimate suggests that up to 380 000 tonnes of carbon could be stored in the affected peat and bog areas, which could be released as construction on this land begins. Together with the 80% increased material requirements of foundations on peat and bog, this can cause a lot of emissions. As a result, my short-term recommendation is that these areas are either preserved as nature reserves or only light structures that do not need a foundation are constructed. In the long-term I recommend that new zoning types for city planning are developed that take soil types into account. Lastly, the effects of soil types should be taken into account in future studies of the material stock in residential housing.

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# 1 Introduction

"Portland cement is the most widely produced human-made material in the world" (Ellis et al., 2019, p. 12584) and this cement is essential to make the world's most important building material: concrete. Not only is concrete the most common material for construction, but it is also one of the largest greenhouse gas (GHG) emission contributors globally. Cement, one of concrete's ingredients, is responsible for about 4% - 7% of annual GHG emissions (Davis et al., 2018; Lehne & Preston, 2018). This is mostly due to 1) the calcination process of the raw material inputs and 2) the high energy requirement of cement making (Norcem, 2022).

It is important to clarify the difference between cement and concrete. Cement is a mixture of mined resources such as limestone, shells or chalk and combined with other ingredients such as clay or slate (Portland Cement Association, 2022). It is mixed under high heat and then ground into a powder. Concrete, on the other hand, is a mix of cement with sand, gravel, and water. These can be mixed in various ratios to achieve different properties, as required for the construction. Concrete is most commonly used for buildings and infrastructure (Lehne & Preston, 2018).

Because concrete is such a large contributor to GHG emissions, it has become relevant to environmental policy makers to reduce national emissions. This is especially important, because the ambitious climate goals of the COP 21 Paris Climate Agreement are legally binding for its signatory states (UNFCCC, 2022). Norway, as a signatory, has transferred some of the goals determined during the conference into national law (Norwegian Ministry of Climate and Environment, 2019). One Norwegian municipality that has set itself goals going beyond those specified in the Paris Agreement, is Trondheim. The city plans to reduce their emissions by 10% by 2020, 30% by 2023 and 80% by 2030, all relative to 2009 emission levels (Trondheim Municipality, 2021). To achieve these ambitious goals, strong emission reductions are necessary. To better plan those reductions the municipality must know where their emissions are coming from. To get a spatial understanding Figure 2.1-1 provides an overview over the 25 neighborhoods in Trondheim.

Being the fourth largest city in Norway, Trondheim is, in 2022, home to around 211 000 people, a number that has steadily increased over the past decades (Statistisk sentralbyrå, 2022). The increasing population has led to entire new neighborhoods being planned and built. This new construction heavily relies on concrete. As concrete's environmental impact is so significant it becomes crucial for the municipality to better understand the flows of concrete and to quantify the emissions related to it. Once they have an overview over the material flows and emission sources, they can enact policies to reduce emissions effectively. One way, for the municipality, to gain insight, is through research projects from universities. One such project is the Circular City project at the Norwegian University of Science and Technology, which is located in Trondheim. The project aims to better understand the existing building stocks' role for future circular economy planning (NTNU, 2023). As the project maps material flows and stocks and better understands the overall system these insights can be used by the municipality to inform its policy making. Due to the widespread use of concrete in building construction and the lack of previous research on concrete use in Trondheim specifically the topic fit into the Circular City project and thus led to the topic of this thesis: An analysis of concrete use in residential building foundations.

This thesis consists of seven chapters. The first chapter is this introduction. In the second chapter I present the research gap, the research question and its sub-questions. In chapter three I provide a literature review to establish an overview over the field and locate this research topic within the literature. In chapter four I explain the methods that I applied for the research. In chapter five I present the results. In chapter six I discuss the results and their implications, and I reflect on the limitations of my research. In chapter seven I summarize the main conclusions of my thesis.

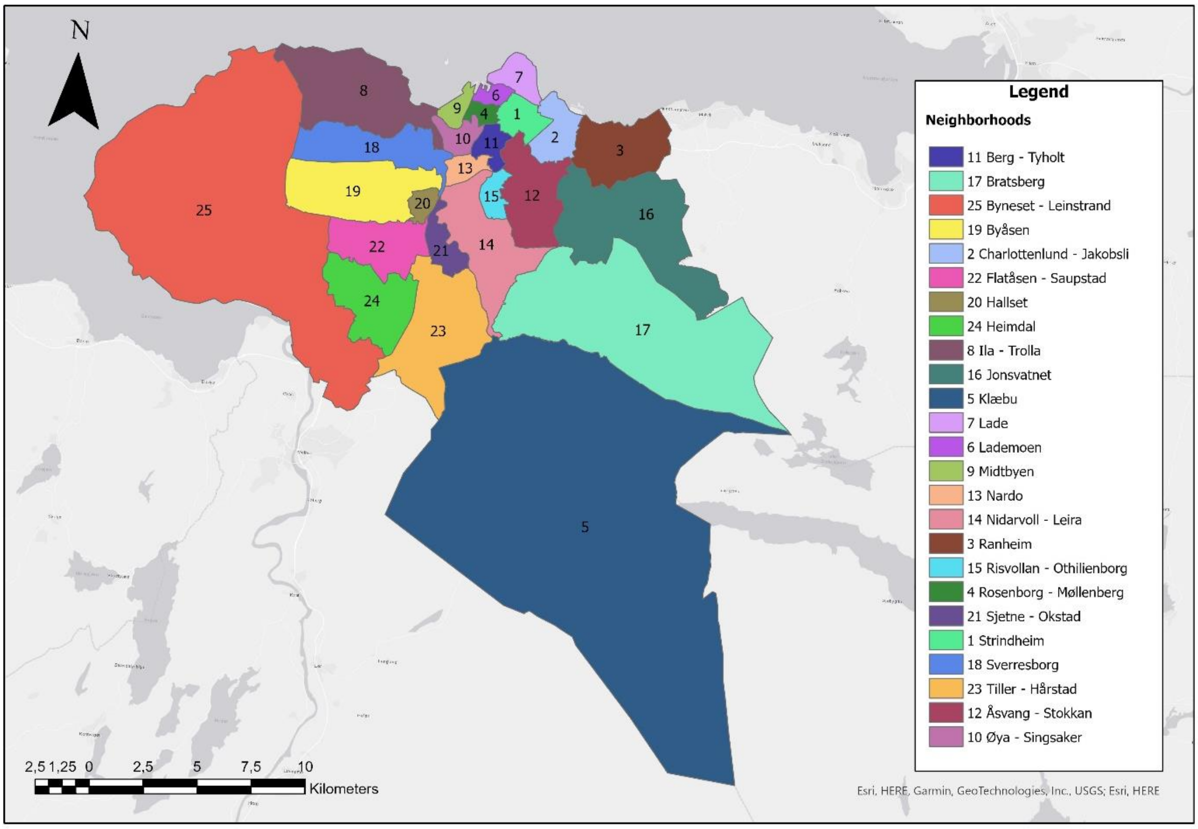


*Figure 2.1-1: A map of Trondheim's neighborhoods (Geodata AS, 2023).*

# 2 Research Gap

Building types have often been disaggregated by their above-ground attributes for more in-depth residential housing material stock analyses. Gontia et al. (2018) disaggregated buildings by their load bearing construction material, like concrete, bricks, or wood. Condeixa et al. (2017) separated by building types, like single-family houses and multi-family houses with 4, 8 and 16 floors. Building foundations, on the other hand, have been mentioned in considerably less detail. Tanikawa and Hashimoto (2009) aggregate several subsurface structures, such as foundations, sewers and the base layer of roadways. However, they assume that these stocks are unlikely to be extracted due to the additional required work and thus deem them less relevant for urban mining than above-ground stocks. Condeixa et al. (2017) consider two types of foundations, raft foundations and deep foundations with Franki piling. However, no further discussion of the foundations and their effects on material intensities (MIs) is done. Gontia et al. (2018) assess MIs in Sweden. They assume a slab foundation for all buildings, omitting foundation pillars of wood or concrete, because only a few buildings in their sample had such foundations and because they assume foundations are unlikely to be extracted after a building's end of life. In their study they find that foundations make up around 60% of a single-family house's entire mass, while for multi-family housing the foundation's mass share is 25%. Similarly, Arceo at al. (2023) assess residential buildings in Toronto, Perth and Luzon. They assume three different foundations, 1) basements in Toronto, 2) slabs in Perth and 3) footings in Luzon. Their results indicate that foundations make up around 70% of the studied single-family homes' masses.

All in all, more recent literature started to differentiate between different foundation types. However, these studies still seem to apply a narrow selection of the different foundation types available today. The selection of the right foundation depends on two aspects: 1) the house it is supposed to carry in the future, and 2) the soil it is built upon (Rajapakse, 2008). Until now, especially this dependence of foundation design on the soil type has not been studied in the residential housing material stock literature, creating a gap in the literature.

To fill this gap, this thesis explores the material requirements of foundations in dependence on the building type and the soil type in the city of Trondheim. I selected the city-level to keep the dataset size manageable for the development of a proof of concept. This also ensures that it is reasonable to assume the same construction technology is used for all buildings. Furthermore, a city-level analysis can strengthen the certainty of the results, as the methodology can be more tightly fitted to local circumstances (Lanau et al., 2019). Moreover, there is a variety of good data sources available for Trondheim. This includes the Norwegian cadaster dataset as well as extensive soil data by the Norwegian Geological Survey. Moreover, the municipality's climate and environment unit is actively interested in research about Trondheim and thus very supportive when contacted with questions.

Foundation construction is guided by 4 geotechnical sections of the Norwegian building code (Standard Norge, 2023). Section one has last been updated in 2008, section two in 2010. Sections three and four have been updated in 2013 and again in 2020. Thus, thesis covers residential buildings built between 2010 and 2020, because it can be reasonably assumed that the same foundation building technologies were used in the timeframe from 2010 to 2020. If the timeframe were extended beyond 2010 then previous building code versions would have to be included for earlier cohorts. Due to the limited time of the thesis project this was not possible. Lastly, the emissions of the last leg transport from the concrete supplier to the construction site are estimated. This situates the emissions of concrete production and transportation in their context and can lead to the identification of emission hotspots. All in all, my thesis project thus adds to the literature on material intensity (MI) and material stocks in foundations. Moreover, I will compare concrete production emissions to last-leg transport emissions to determine their individual contributions.

## 2.1 Research Question

To fill the gap in residential building foundation literature I completed four steps: First, I determined the amount of concrete that has been used in Trondheim's residential building foundations that were built between 2010 and 2020. Next, I calculated the emissions from producing the required concrete. This includes concrete manufacturing emissions as well as transport emissions from the supplier in Trondheim to the construction site. Third, I explored how the house type and the soil type affect the material requirements of a building's foundation. Lastly, I discussed how the results may be useful for Trondheim's policy makers. To guide my study the research question asked:

*What are the material stock additions of concrete and its related emissions in Trondheim from residential building foundations built between 2010 and 2020?*

The guiding sub-questions asked:

1) *How much concrete was added to the material stock?*
2) *What are the GHG emissions from producing and transporting the concrete?*
3) *How do the building type and the soil type affect the material requirements of a building foundation?*
4) *How can the results be used by policy makers of the Trondheim municipality?*

It is important to note that this research does not include concrete requirements for the current stock maintenance. Rather, it specifies the stock addition and related emissions from the additions of residential building foundations constructed between 2010 and 2020. The following chapter presents the academic context of this research and introduces different methodological approaches from this field.

# 3 Literature Review and Relevant Theory

Research shows that around 40% of all materials used in society are currently found in the residential building stock (Gontia et al., 2019; Gursel et al., 2014). This insight is mostly derived through the research method of Material Flow Analysis (MFA). A theoretical introduction to the field is given in the following sections.

## 3.1 Material Flow Analysis

The concept of tracing material flows and where they end up, so-called stocks, is inherent to the method of Material Flow Analysis. MFA has its roots in the concept of mass balance, which states that any material inflow must either flow out or must be stored in a stock. Thus, knowing the inflows and outflows of a system, one can calculate the net stock addition. MFAs are conducted within a defined system boundary. Within this system all stocks and flows of the material in question are mapped and tracked. Depending on the system, it is possible to have flows cross the system boundaries.

Studies are conducted at different geographic scales. They can range from the neighborhood level all the way to the global scale (Lanau et al., 2019). The scale defines what geographic area is considered in the research. The spatial resolution, on the other hand, indicates the level of spatial detail that can be found within the chosen geographic scale (Lanau et al., 2019). For example, a study with the geographic scale of a city, could have results at the city level, so low resolution, or at a per $m^2$ level, so a high resolution.

Krausmann et al. (2017) for example tracked the extraction of 10 materials at the global scale and over time and found that recycling only contributes 12% to annual material use in stocks. Moreover, they calculated that material stocks had increased 23-fold between 1900 and 2010 and that “about half of all materials extracted globally by humans each year are used to build up or renew in-use stocks of materials” (Krausmann et al., 2017, p. 1880). As they focus mostly on the global level, only differentiating between 3 groups, industrial countries, China and the rest of the world at times, their spatial resolution can be considered low.

At the national scale material stocks and flows are assessed only within the selected country. This focuses the research significantly compared to the global level. An example is the paper by Zhang et al. (2015), who assessed copper flows in China. They found that while copper extraction is highest in the western provinces, the copper stocks are found in the eastern provinces, where China’s large urban areas are located. As their assessment takes place at the province level, their spatial resolution is considerably higher than that of Krausmann et al. (2017). However, given the context of Zhang et al.’s (2015) lower scale, the national level, their spatial resolution is still low in comparison. The paper by Tanikawa et al. (2015) on the construction material stock of Japan also uses the national scale. However, their results are presented per $km^2$, so a very high spatial resolution.

Zooming in further, another common scale is the city level. A narrower focus can bring advantages, such as more location-specific considerations. On the other hand, a narrow focus may also reduce the generalizability of results, because the study’s approach has been fitted to the specific city. An example of an MFA with city-level system boundaries is the material stock assessment of Vienna by Kleemann et al. (2016). In their study they used a GIS-based approach to estimate the material stocks of minerals, organic materials and metals. They concluded that minerals, including concrete, make up more than 96% of Vienna’s material stock. This is very useful to know when developing urban mining plans, for example.

Moreover, MFAs can be static or dynamic. Static MFAs assess the material stock at a certain point in time, like, for example, Kleemann et al. (2016) in Vienna. This snapshot assessment can be repeated to track stock changes over time. An example of this can be seen in Tanikawa et al. (2015) for a study from 1945 until 2010. For dynamic MFAs, on the other hand, the stock at a given time is the result of the in- and outflows from previous periods. The material inflows are assigned lifetimes, often with a statistical distribution. As materials flow into the stock over time the stock starts to grow. The stock is then a function of the newest inflow plus the sum of all previous inflows minus the outflows. If inflows are larger than outflows the stocks grows, if the inflows are smaller, the stock decreases. An example is the research by Pauliuk et al. (2013). They estimate iron stocks in 200 countries around the world from 1700 until 2008 and found that in some highly industrialized countries, like Germany or the United Kingdom, stocks are actually leveling off, meaning they are no longer, or only slowly, increasing. This is an important insight when estimating future steel production and scrap availability, and therefore useful for circular economy planning.

Lastly, MFAs can be retrospective or prospective. Retrospective analyses look at past developments, without extrapolating into the future. Such studies are, for example, the assessment of steel stocks in the world from 1800 until 2010 by Krausmann et al. (2017). Prospective MFAs, on the other hand, try to extrapolate stocks and flows into the future, often considering a variety of different scenarios. A widely known paper that did so with urban stocks was written by D. B. Müller (2006) and has since served as the foundation for the research field of prospective urban metabolism research. Another example would be the paper by Vásquez et al. (2016), which assessed energy reduction strategies in Germany and Czechia.

## 3.2 Urban Metabolism Research

The study of the urban metabolism, especially its stocks, roughly began 40 years ago. In the 1940s Ostrolensk (1941) recognized that the current material stocks will become future material sources once they have reached their end of life. It took, however, another 40 years until this insight was further researched. Until the early 2000s in fact, the focus of studies was mostly on flows. Stocks, on the other hand, played a rather minor role (Lanau et al., 2019). Since the mid-2000s, however, the research shifted to also include stocks. Moreover, a number of new approaches to study stocks and flows were developed, for example remote sensing or GIS-based methods.

Based on their number of publications, Müller and Tanikawa are two influential authors in the field of built environment stocks (Lanau et al., 2019). In the mid-2000s Müller developed a model calibrated with data from 1900 until 2003, which allowed him to project the Dutch housing stock from 2003 until 2100 under three different scenarios (D. B. Müller, 2006). His approach was breaking ground on using external factors, such as population, people per dwelling and building lifetime estimates as drivers for material stocks and flows. Some important key findings of this paper were that construction and demolition flows are cyclical. Moreover, a growing stock increases flows even more rapidly, as the inflow is not only increasing the stock, but it must also cover material needs to maintain the stock, such as repairs. This means, even a large stock that is not growing might have considerable inflows, just for its maintenance.

Another influential author is Tanikawa. He is most active in the field of spatially explicit, Geographic Information System (GIS) based MFAs of the urban metabolism. A key paper in this regard was the publication of Tanikawa and Hashimoto (2009). It introduced a dynamic GIS-based approach, as they called it, a 4D approach, including time as the fourth dimension. Tanikawa and Hashimoto used this approach for their research where they assessed Salford in Manchester, UK and Wakayama Center in Japan. They found that in Wakayama City 47% of the total stock was used in underground infrastructure. This was significant, as underground material stocks are still largely underexplored. In 2015, Tanikawa published another important paper, this time assessing the material stock in all of Japan from 1945 until 2010 (Tanikawa et al., 2015). This was a significant new addition to the literature due to the large timeframe and scale they covered for a bottom-up GIS approach. The bottom-up approach is explained in the following section. Both papers served as the foundation for many more GIS-based studies and were also highly relevant to this research project.

### *3.2.1 Approaches to Urban Metabolism Research*

Generally, there are three methods to estimate the stocks and flows in an urban environment: 1) a bottom-up approach, 2) a top-down approach or 3) remote sensing.

The bottom-up method uses a case-study like approach to estimate material stocks. By estimating the material contents of an archetypical object of study, its MIs are calculated. These indicate the typical material content of the object. Once these MIs are defined one can determine the material stock by multiplying the MIs with the number of objects found in the area of study, thus building a stock estimate from the bottom up. An advantage of a bottom-up approach over a top-down approach is its high spatial resolution. This allows for the better differentiation of different material contents. Moreover, because the results are “directly derived from information on stock inventory, results of bottom-up studies are usually deemed to be more accurate than those obtained through a top-down approach” (Lanau et al., 2019, p. 8505). However, the bottom-up approach is limited in its applicability to objects of study that examine a degree of homogeneity due to the need of defining archetypical objects for MI development.

In a top-down approach stock estimates are based on historical inflow data (E. Müller et al., 2014). These can often be provided by statistical agencies, industries, or non-governmental organizations. The advantage of a top-down approach is that it allows for the establishment of an overview over stock levels. This is, because there are often long-lasting accounts back in time from national sources, which allow the studies to cover large timeframes (Lanau et al., 2019). However, the spatial resolution of top-down analyses is often limited to the national level, because this is the most common level at which statistical agencies collect data. Given the right data, however, top-down approaches at lower levels are also possible. Additionally, a crucial source of uncertainty is the limited knowledge on product lifetimes and other factors (Lanau et al., 2019).

Another approach to estimating material stocks are remote sensing methods. Most popularly nighttime light images taken from satellites are used. With the help of statistical models, researchers then approximate material stocks based on the light emissions in the image. An example of such an approach can be found in the paper by Peled and Fishman (2021), who have estimated the material stocks of Europe.

## 3.3 Challenges of Material Intensity Factors

A common problem throughout the literature has been uncovered by Lederer et al. (2021). Most studies, they found, opt to determine an MI factor which is then multiplied by the building dimensions. However, Lederer et al. (2021) criticize how this MI factor is determined. In studies they investigated they found that MIs were calculated by selecting a few buildings of a subset of the population and calculating a MI factor for them. However, in their view, the sampling of the examined buildings is not done at a representative level and not randomly enough. This complicates the comparison of results across papers further, because of two reasons. First, the assessment methods of buildings vary from study to study. Some studies conduct on-site examinations. These, however, also vary widely in their levels of detail. Second, studies select unrepresentative sample sizes, so their MI factors are, statistically speaking, not representative. Lederer at al. (2021) thus set out to find a representative sample of buildings in Vienna. They used random stratified sampling to select a representative sample among 72 different building categories. Their results indicated that random sampling to determine MI factors does increase the representativeness of their results. However, they acknowledged that this is not always possible due to lacking data. In fact, they themselves had to reduce their sample size from initially 1% (2,265) of all buildings (226,482) to 0.1% (226), due to the significant amount of work necessary to assess that many buildings. They concluded, however, that their results improved on previous assessments of Vienna's building stock by Kleemann et al. (2016). Sprecher et al. (2022) started a first attempt at creating "big data" MIs, by analyzing data from 61 demolition projects, providing 781 datapoints. This resulted in one of the data-richest MI factors in the literature. However, the big disadvantage is that data collection during the demolition process only allows for the assessment of older buildings. More modern buildings' MIs, which are not demolished for a while, are still difficult to assess with this method.

Another challenge when developing MI factors is their temporal adaptation (Ajayebi et al., 2021). As soon as longer periods of time are under investigation it is reasonable to assume that building practices changed over decades. In fact, several studies investigated this and found variations across decades (Ajayebi et al., 2021; Bergsdal et al., 2007; Mastrucci et al., 2017). As a result, if longer periods of time are being assessed, it is important to develop a dynamic MI factor, which adjusts according to the time.

A lack of common reporting standards for MIs is yet another challenge in the literature (Gontia et al., 2018; Sprecher et al., 2022). This complicates the comparison of MIs between different studies and their re-use on larger scales. Efforts have been made to harmonize the MIs of various papers such as the attempt by Heeren and Fishman (2019). They compiled a database with 301 data entries from 33 studies, which is accessible on GitHub and open for contributions from other researchers to keep on growing and developing. Unfortunately, the last contribution to this project on GitHub was in 2020 (as of September 2022). While there seems to be a consensus in the literature that common databases and standards should be established this would, however, hint that the efforts to truly achieve this are limited. Also, Gontia et al. (2018) had to harmonize various MIs found in the literature to compare them with the results they found in their study. They found that their case study, Sweden, had higher use of wood and steel compared to other studies. This, supports the notion of Hu (2010), that the Nordic countries, Norway, Sweden and Finland, rely more heavily on wood constructions. Lastly, harmonized MIs enable studies like the one by Marinova et al. (2020). They assessed the global construction stock of residential buildings from 1970 to 2050. For their research they had to combine MIs from over 56 studies, something that would have been significantly easier if common reporting standards would exist for MIs that were collected in a common database.

## 3.4 Concrete in Built Environment Research

The widespread use in the construction sector and the considerable environmental impact of concrete makes it a commonly studied material. In fact, in around 60 publications of the database created by Heeren and Fishman (2019) include at least one MI factor for concrete. Often concrete is studied in combination with other building materials (Bergsdal et al., 2007; Kleemann et al., 2016; Tanikawa et al., 2015). This provides a better insight in the materials' relational uses and supports comparability, because it is more likely that the materials were studied employing the same methodology. An exploration of concrete was conducted by van den Berghe and Verhagen (2021). They analyzed concrete factory locations and transport distances in The Hague to assess spatial planning requirements for a circular city. They found that to ensure the circular use of waste concrete it is important to keep concrete factories within the city limits to ensure all concrete can be processed in time for reuse. Research has also established that waste concrete has several options for reuse such as downcycling it for road foundations or reusing it to partially substitute virgin aggregate material in concrete mixes (Lotfi et al., 2015; C. Zhang et al., 2018).

## 3.5 The Geographic Approach

In the geographic approach geospatially referenced data can be analyzed and compared spatially to each other. That means the analyzed data can be attributed to specific locations in the real world. This data analysis can create maps which help visualize complex data relationships and are especially useful for decision makers (Esri et al., 2009; Göswein et al., 2018). Göswein et al. (2018), for example, use it to assess the locations and supply chains of different types of concrete to explore whether their transport emissions are relevant to overall emissions, when selecting between different types of low-carbon concrete mixes. Kleemann et al. (2016) use the geographic approach to assess the material stock of buildings in Vienna. Tanikawa and Hashimoto (2009) explored the material stock in buildings in Wakayama City (Japan) and Salford Quays in Manchester (UK) across time. This spatial explicitness is not only useful for the assessment of geographic differences, but also useful for policy makers or industries.

# 4 Methodology

In the following chapter the used methods and data requirements are explained. The research was conducted relying on 1) a geographic approach and 2) the development of two Python models. The geographic approach was used to explore and analyze the geospatial data, like identifying the location of housing and of the various soil types found across Trondheim. The two models were used to 1) estimate the concrete requirements of the residential building foundations from 2010 to 2020 and 2) to estimate the transport distance from the four concrete suppliers in Trondheim to the construction sites of the new buildings. From that I could estimate 1) the concrete stock additions from foundations in the last 10 years and 2) the emissions from producing this concrete as well as the last-leg transportation. Figure 3.5-1 visualizes how the different methodological approaches interact with each other to contribute to the final outcome.

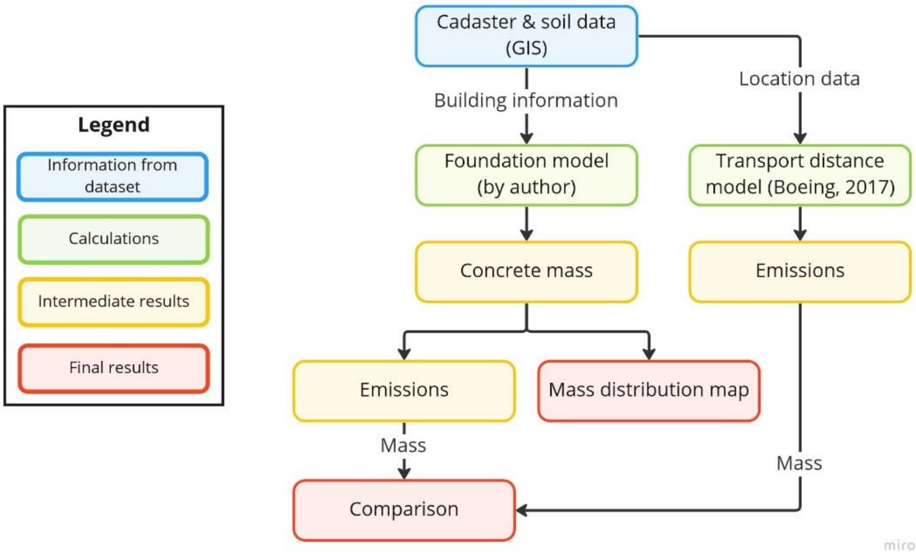


*Figure 3.5-1: Overview of how the different approaches interact with each other. Cadaster data from Geodata AS (2022) and soil data from NGU (2022).*

The geospatial analysis and database creation in ArcGIS Pro and the two models are explained in detail in the following sections. The sections are structured to explain 1) what method is used, 2) what data is needed, 3) how the data was processed.

## 4.1 Geospatial Analysis in ArcGIS Pro

To conduct the planned analysis, specific data on each building in Trondheim are required. Such data includes information on the location and building specific information of each house as well as the location of the various soil types across Trondheim. The most fitting approach to organize, manage, and analyze such a mix of spatially explicit data is the geographic approach. The software used was ArcGIS Pro.

### *4.1.1 Data Requirements*

The goal of the method is to determine the geographic location of each building and a list of its specific information, which can be found in Table 4-1. These data are later used by the foundation model. There are five different building types (see Table 4-2). I developed these by summarizing the 30 different residential building categories that can be found in the original dataset from the Norwegian statistical agency that were developed in 2000 and still apply (Statistisk sentralbyrå, 2000). An example of such a summary is the combination of vertically split semi-detached houses and horizontally split semi-detached houses into one group. Irrelevant building types were excluded from the analysis. These include cabins, because they are often built on lighter foundations due to the low above-ground structure mass. It also includes garages, which are part of the residential building category in the cadaster dataset but are not used for living and are thus excluded. The aggregation of the house type data is important to prepare them as inputs for the models for foundation and distance calculations as well as for the visualization of the results at the end.

*Table 4-1: Information required for each building.*

| Data points |
|---|
| 1) Building type<br>2) Year of construction<br>3) Building footprint<br>4) Useful floor area<br>5) Number of basement floors<br>6) Soil type under the building |

*Table 4-2: The five relevant building types with their building code in brackets. Building types were developed by me by summarizing the 30 official categories specified by the Norwegian statistical agency(Statistisk sentralbyrå, 2000).*

| Building type (building code) |
|---|
| Single family house (110) |
| Semi-detached house (120) |
| Rowhouse (130) |
| Apartment building (140) |
| Assisted & communal living (150) |

The information on datapoints 1) to 5) in Table 4-1 was sourced from Geodata AS (Geodata AS, 2022). Valid login details are needed to access the data. Geodata AS is an experienced company that offers maps and other services for Esri costumers in Norway. They got the data from the Matrikkel, the Norwegian cadaster dataset. The Norwegian cadaster is created and maintained by Kartverket, Norway's official mapping agency. They, in turn, are collecting the data from the municipal governments. The soil type data is sourced from a dataset called "Løsmasser" ("Sediments" in English) from the Norwegian Geological Survey (NGU, 2022). Table 4-3 provides an overview of all soil types found in Trondheim.

*Table 4-3: Overview of all 15 different soil types found in Trondheim (NGU, 2022). The soil type names were translated from Norwegian to English by the author.*

| Soil type |
|---|
| 1. Under water |
| 2. Moraine material, continuous cover, in places with great strength |
| 3. Moraine material, disjointed or thin cover over the bedrock |
| 4. The marginal moraines/marginal moraine zone |
| 5. Glacifluvial deposition (glasifluvial deposition) |
| 6. Sea and fjord deposition, continuous cover, in places with great strength |
| 7. Marine beach deposition, continuous cover |
| 8. Sea, fjord and beach deposits, disjointed or thin cover over the bedrock |
| 9. River and stream deposition (Fluvial deposition) |
| 10. Weathering material, disjointed or thin cover over the bedrock |
| 11. Peat and bog |
| 12. Thin cover of organic material over bedrock |
| 13. Fill mass (anthropogenic material) |
| 14. Human-influenced material, not further specified |
| 15. Bedrock |

### *4.1.2 Data Treatment*

The data were processed in three steps. First, the housing data was plotted on the map. This creates a polygon shape for each house at its respective coordinates. Second, the soil type data was plotted on the same map, resulting in larger polygon shapes that encompass various houses. In a third step, a spatial join was applied, by which the center point of each housing shape is taken as the deciding factor. If the center point is in the polygon of soil type A, the house is assigned soil type A, if the center point of the house is in the polygon of soil type B the house is assigned soil type B. Figure 4.1-1 visualizes this concept. This means, that while in reality a house may be built on two types of soil, depending on its plot of land, this model assumes only one type of soil for every house. Figure 4.1-2 shows the aggregation of the spatial data in the GIS database and how it is later connected to the foundation model and the distance model.

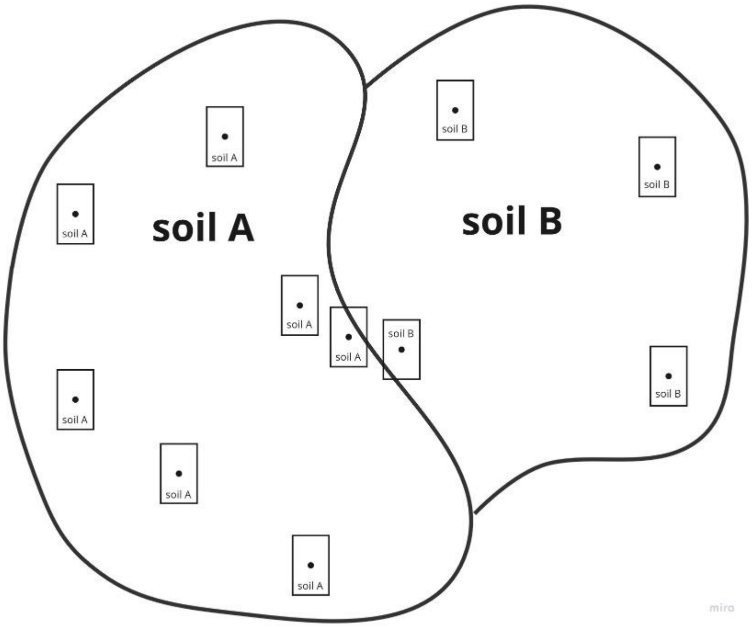


*Figure 4.1-1: Visualization of the spatial join function in ArcGIS Pro based on a shape's midpoint.*

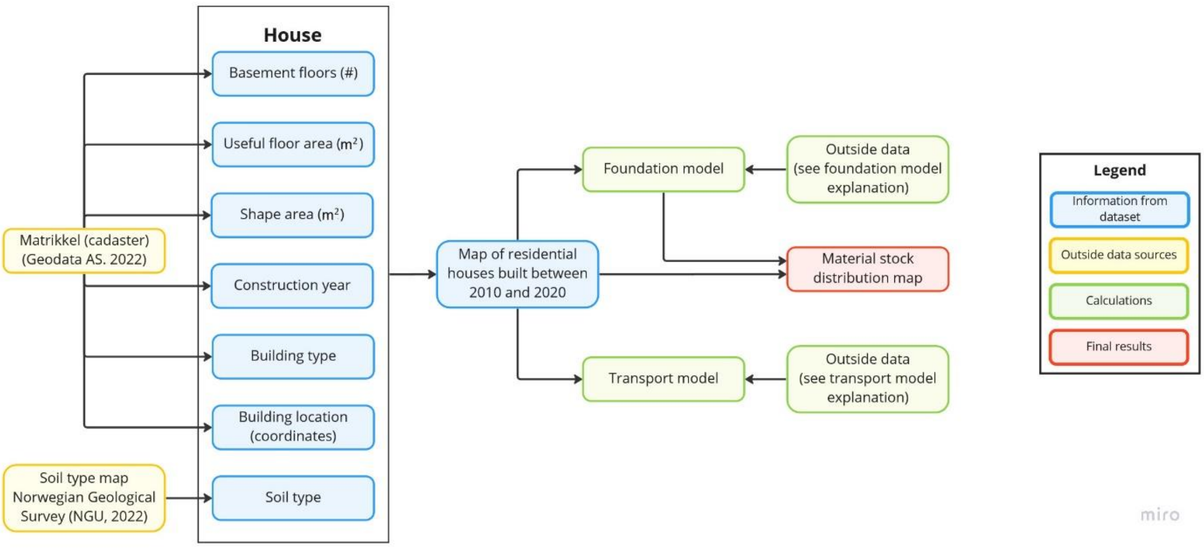


*Figure 4.1-2: Overview of data use from the Geographic Approach.*

## 4.2 Model Building

The transport distance model makes use of Open Street Maps libraries and functions developed by Boeing (2017) to determine transport distances. For the foundation model, on the other hand, the author is not aware of any other models or libraries with the same functionality. It was thus developed by the author specifically for this thesis.

### *4.2.1 Foundation Model*

Once the location of each house is determined it must be established how much concrete is in its foundation as well as the emissions produced from making the required concrete. By connecting the material volume and its production emissions to each house, they can be spatially attributed across the city.

Initially the plan was to gather primary data from producers and construction companies. However, establishing contact with the relevant companies proved difficult and where contact was successfully established there was no possibility to receive data. Because of that, the material stock levels had to be determined differently. Foundation design of buildings is a standardized process. They are built under ground and are thus not visible. Due to foundations' functional nature a few best practices with archetypical foundation types exist. As this substantially reduces the variability of foundations across different buildings, a model can be developed. The model uses several formulas from structural engineering to determine a foundation with sufficient bearing capacity. From that the required amount of concrete and the resulting concrete production emissions can be determined.

#### 4.2.1.1 Data Requirements

To estimate the foundation of a building the model requires six general data inputs. First the specific data of the building for which the foundation should be estimated is extracted from the dataset that was prepared as part of the geographic approach. This dataset is the "map of residential buildings built between 2010 and 2020" as shown in Figure 4.1-2. The following paragraphs elaborate on the required data inputs.

The building type information must be retrieved because the building's size affects the type of foundation. Generally, shallow foundations are preferred when planning a foundation, because they do not reach deep into the ground and are thus less material demanding and more cost effective (Rajapakse, 2008). Therefore, I am assuming shallow foundations are used for the smaller buildings (code 110 through 130). On stable grounds, like bedrock, taller buildings (140 and 150) can have a shallow foundation too (Dr. A. M. Selberg, personal communication, 1.12.2022). However, in less stable soils taller buildings (140 and 150) require deeper anchoring in the ground due to their own weight and stronger exposure to above ground forces such as wind. Thus, I am assuming deep pile foundations in those cases. For an exact overview see the Supporting Information.

Another important aspect is the soil type the building is built upon. For example, stable grounds such as bedrock require different foundation types than unstable grounds like peat soil. By feeding the soil type into the model, this can be linked with 1) the type of foundation that will be used for that building and 2) the soil specific data, which is required for the engineering formulas.

Furthermore, the number of basement floors is considered, as this will 1) add additional material requirements to a building foundation due to the construction of walls and 2) affect the type of foundation that is required, because a basement provides structural stability due to its high walls. Thus, deeper foundations may not be necessary anymore. The area which must be supported by the foundation is taken from the surface area value, also called footprint, of the building. It is also used to calculate the loads the foundation needs to take up. It is important to note a few aspects with regard to buildings with basements. First, a basement is generally built with a slab foundation, no matter the soil type, because the depth of the basement delivers enough stability to the building. Additional foundation structures are only required in peat and bog soils due to the lack of bearing capacity. Furthermore, both, buildings with an official basement and buildings with a so-called "underetasje", a basement that is somewhat halfway built into the ground, are considered to have a basement, because it also serves a stabilization-providing role (see Figure 4.2-1).

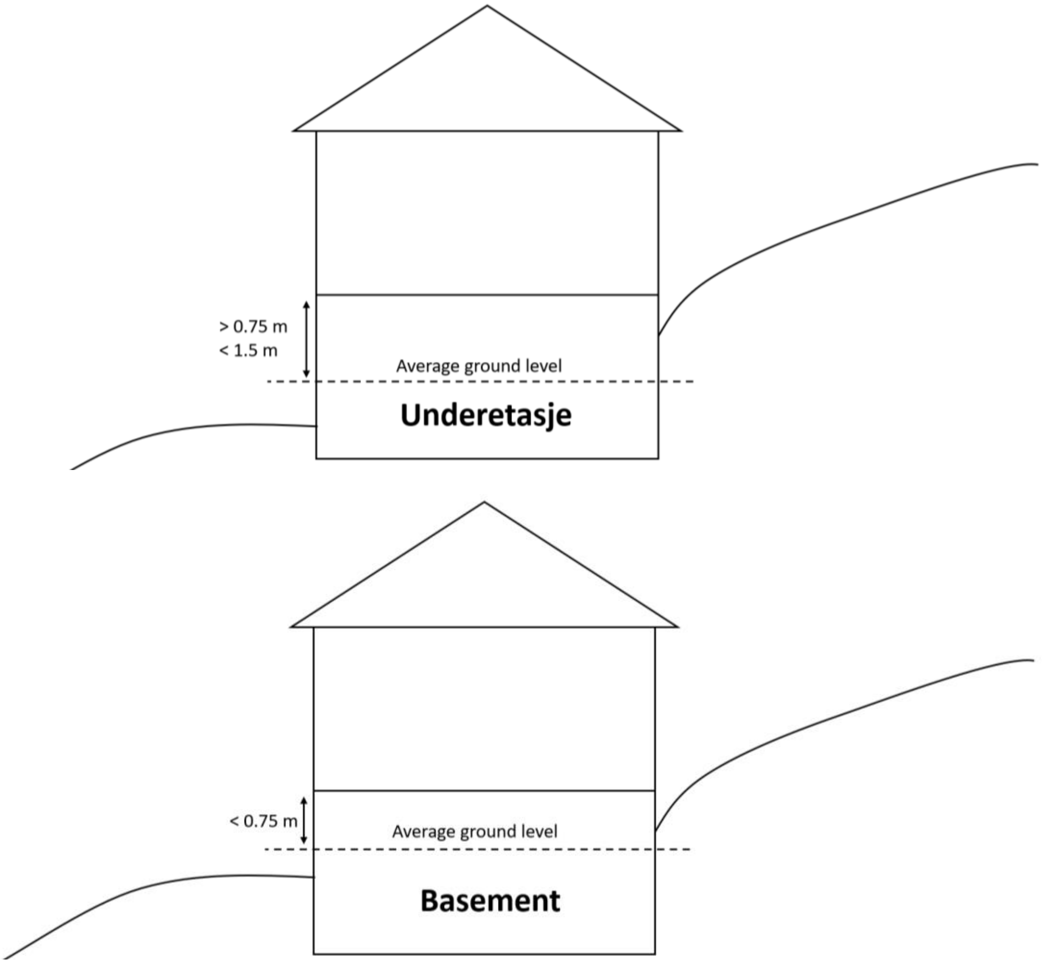


*Figure 4.2-1: Visualization of an "underetasje" and a basement, showing their similarity. Underetasjer are simply a basement that comes higher out of the ground (Kartverket, 2023).*

Another crucial aspect is the weight of the building, as this determines what stresses the foundation must be able to withstand. To calculate the building weight a material intensity factor from a paper by Gontia et al. (2018) analyzing material intensities in Sweden is taken. This is justifiable, as both Norway and Sweden share similar construction methods and building types due to geographic proximity and shared history. The paper by Gontia et al. (2018) produced two material intensity coefficients, one for single-family houses at 350 kg/m$^2$ gross floor area and one at 944 kg/m$^2$ gross floor area for multi-family buildings. For small buildings Gontia et al. attribute 60% of the material intensity factor to the foundation, leaving 40% of it to determine the building weight. For large buildings they attribute 25% to the foundation, thus leaving 75% of it for the building weight calculation. These are thus used accordingly, by assigning single-family, semi-detached and rowhouses to small buildings, while apartment buildings and assisted and communal living are considered large buildings. The material intensity factor is multiplied with the useful floor area (UFA) of the building in question to get an approximation of the building's weight.

The model also requires information on what foundation types are available and which one will be used for which house. This information was sourced from academic and gray literature (websites and videos) resulting in five archetypical foundation types (Abebe & Smith, 2022; AF Math & Engineering, 2018; HGC India, 2018; Rajapakse, 2008; The Constructor, 2020; Tomiša, 2019; Turskis et al., 2016). These are 1) the slab foundation, 2) the basement, 3) the spread footing foundation, 4) the strip foundation and 5) the deep pile foundation (see Figure 4.2-2).The selection was predominantly based on which foundation types were mentioned the most often across all sources. I also ensured that always at least one of the selected foundation types could be built on the soils found in Trondheim, so that a foundation can be matched to every house in my dataset. The foundations were discussed with Dr. A. M. Selberg and Dr. T. Kanstad and then used in this model (personal communication, 1.12.2022 and 5.12.2022 respectively). Important to note is that the model always assumes square shaped building footprints on an even ground. Therefore, the results mark the lower end of the range of required concrete volume.

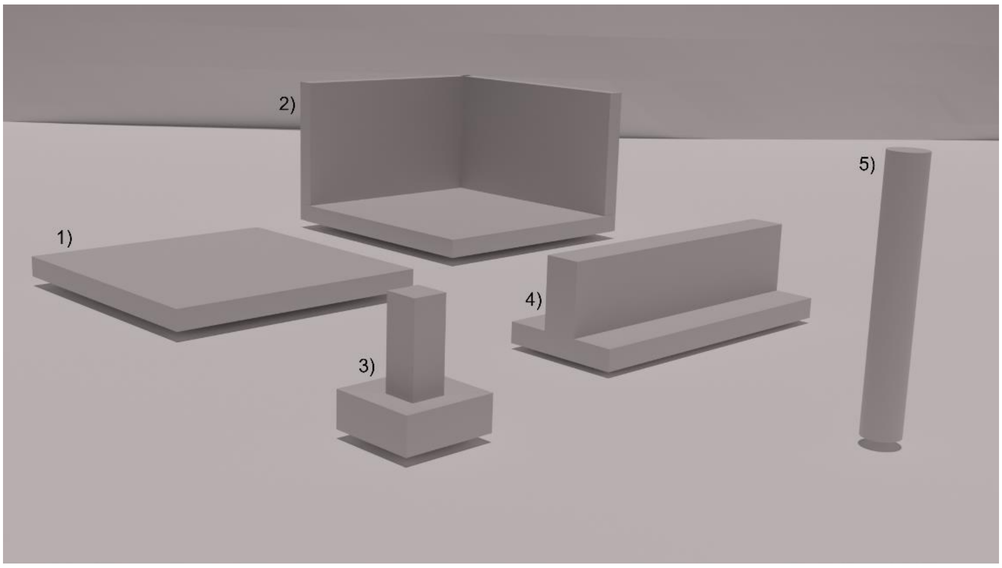


*Figure 4.2-2: Visualization of the five foundation types. From left to right is 1) slab, 2) basement, 3) spread footing, 4) strip, 5) deep pile foundation (image made by the author).*

Crucial to the model are the formulas for estimating a foundation's bearing capacity in a specific soil. This includes separate formulas for deep pile, strip, and spread footing foundations. The formulas were taken from the engineering handbook *Geotechnical Engineering Calculations and Rules of Thumb* by Rajapakse (2008). Crucially, certain dimensions for these foundations had to be assumed to make the calculation feasible. For example, a standard end-bearing deep pile was assumed to be 5 meters long and have a diameter of 0.5 meters. This was motivated by a study by Long et al. (2022) from which it can be estimated that Trondheim's peat and bog layers are on average about 4.7 meters deep. An end-bearing deep pile works by reaching through the weak soil layer until it reaches a stronger soil layer underneath, thus bearing all the building weight on its ends. The alternative are friction piles, which hold the building weight due to the friction on the pile's surface with the surrounding soil. Such piles are used when no strong soil layers are below the weak soil layer (Rajapakse, 2008). Because the peat and bog layer is about 4.7 meters deep, I assumed stronger soils underneath, leading me to choose end-bearing piles. Assumptions like these were necessary, as a specific design of the foundation parts for each building was not feasible. For basements it was assumed that they always cover the entire area under the house and that they are uniformly 2.5 meters high. Bearing walls other than the ones on the building perimeter were not considered, due to a lack of case specific data. Moreover, it was assumed that smaller buildings, so single-family-, semi-detached- and rowhouses do not have a concrete ceiling on top of the basement, because smaller buildings are light enough that a cheaper material, like wood, provides sufficient bearing capacity. Larger buildings like apartment buildings and assisted and communal housing, on the other hand, have a concrete ceiling on top of the basement to support the heavier building. This was determined in communication with Dr. A. M. Selberg and Dr. T. Kanstad from the structural engineering department at NTNU (personal communication, 1.12.2022 and 5.12.2022 respectively). For slabs it was assumed that they cover the entire area under the house and have a thickness of 0.1 meters for smaller buildings and 0.2 meters for larger buildings. This assumption is, again, based on personal communication with Dr. T. Kanstad as well as the Norwegian building code on fire safety (personal communication, 05.12.2022; Standard Norge, 2010).

The formulas for estimating the foundation's bearing capacity require four specific soil values, 1) the soil friction angle, 2) the soil density, 3) the wall friction angle and 4) the soil's bearing capacity. Usually, soil samples are taken at every construction site, to determine the exact indicators for the soil on site. Unfortunately, this data is not centrally collected. Therefore, characteristic values for the soil types found in Trondheim were researched.

The soil friction angle measures the ability of the soil to withstand shear forces. The data was taken from the website Geotechdata.info (2013), who references sources such as Swiss Standard and various academic publications. The wall friction angle is a value for deep pile foundations and can be calculated from the soil friction angle through a formula provided by Rajapakse (2008).

Soil density represents the mass per volume of soil. This data was taken from five sources. 1) Struct X (2022), a website, get their data from various academic publications, 2) Jones (2018) is a researcher at UBC's Department for Earth and Ocean Science, 3) Sharma (1997) published a book, 4) Aqua-calc (2022) which is a website that does not reference any sources, and 5) Dream Civil (2022), a website and online magazine that write articles about civil engineering. For exact information which source supplied which datapoints see the Supporting Information.

Lastly, the soil's bearing capacity indicates the maximum stress per area on the soil before structural failure. The point of the foundation is to artificially increase this value by, for example, spreading the downward stress of the building over a greater area on the ground. The data on soils' bearing capacities was taken from Geotechdata.info (2015).

Besides the soil type specific values, the formulas also require a number of constants that are dependent on either the soil type's friction angle, or the foundation type, for example whether a pile is round or squared, or whether a pile is bored or driven into the ground by ramming. I assumed square footings for spread footing foundations and round, driven deep piles for deep pile foundations. These specific constants are taken from tables provided by Rajapakse (2008). Table 4-4 provides an overview of all the data needed to run the model.

*Table 4-4: Overview of all data points used in the foundation model. The levels indicate what is contained in a category.*

| Level 1 | Level 2 | Level 3 | Source |
|---|---|---|---|
| Building information | Building type | 110: Single family house<br>120: Semi-detached house<br>130: Rowhouse<br>140: Apartment building<br>150: Assisted & communal living | Geodata AS (2022), modified by me |
| | Soil type | 15 types (see Table 4-3) | NGU (2022) |
| | Number of basement floors | From 0 to 2 floors | Geodata AS (2022) |
| | Building footprint | | Geodata AS (2022) |
| | Building weight | Swedish MI * Useful floor area (UFA) | Swedish MI: Gontia et al. (2018)<br>UFA: Geodata AS (2022) |
| Foundations | Slab foundation | See Appendix B | T. Kanstadt, personal communication, 5.12.2022 |
| | Strip foundation | | Assumed by me, after consulting T. Kanstad (personal communication, 5.12.2022) |
| | Spread footing foundation | | Assumed by me |
| | Deep pile foundation | | By me, based on insights from Long et al. (2022) |
| | Basement | | Based on basement in own house, though house was built before 2010. |
| Bearing capacity formulas | Terzaghi bearing capacity formula | Shallow foundation formulas | Rajapakse (2008) |
| | | Deep pile foundation formula | Rajapakse (2008) |
| Soil type specific data | Soil friction angle | See Supporting Information | See Supporting Information |
| | Soil density | | |
| | Wall friction angle | | |
| | Soil bearing capacity | | |
| Constants | Formula constants for specific soil and foundation types | See Appendix A | See Appendix A |
| | Foundation dimensions | See Appendix B | See Appendix B |

#### 4.2.1.2 Data Processing

The model takes all the above data and approximates the required concrete as well as the produced emissions from concrete production for each building in 8 steps (see Figure 4.2-3). The calculation is done on a case-by-case basis. That means, the model looks at each building independently from the rest of the dataset. It starts by gathering the descriptive data of the case. First, the housing type of the selected house (see Table 4-2), and the soil type it is standing on (see Table 4-3) are determined. Then the number of basement floors are registered. This value can range between 0 and 2. From these three datapoints a foundation is determined based on a lookup table. There, all possible combinations were assigned a foundation type by the author. The model then selects the required formulas for the chosen foundation, gathers the soil specific values and constants and estimates the house weight from the house's useful floor area and the Swedish material intensity factor. With all the values collected, these are inserted into the Terzaghi bearing capacity formula for either shallow foundations or deep pile foundations, depending on the foundation type. The Terzaghi bearing capacity formulas were developed by Karl von Terzaghi, an Austrian geotechnical engineer. I selected them, because they were used by the geotechnical book by Rajapakse (2008), the book I used as the basis for this model. A more detailed explanation of the formulas can be found in Rajapakse (2008). The Python script of the model can be found in the Supporting Information.

Once a foundation with sufficient bearing capacity has been calculated, the dimensions are taken to calculate the total volume of concrete required. A material intensity factor can be calculated by dividing the concrete volume of the house by its UFA. Later, an average of each house's material intensity factor can be taken to get the overall material intensity factor. By multiplying the concrete volume with a conversion factor from volume to mass, 2400 kg/$m^3$ concrete, this is converted to mass, which is more commonly used in the built environment material stock literature. By furthermore multiplying the volume of concrete with an emission factor, the emissions resulting from concrete production can be estimated. This emission factor was taken from Ecoinvent v3.9 and was developed for Switzerland (Werner & Ecoinvent Centre, 2022). Due to the absence of a Norwegian emission factor, this one was deemed to be the closest match due to similar technological and natural conditions in the two countries. It assumes 210 kg $CO_2$ eq. per $m^3$ concrete. Figure 4.2-3 summarizes the data flow of the foundation model.

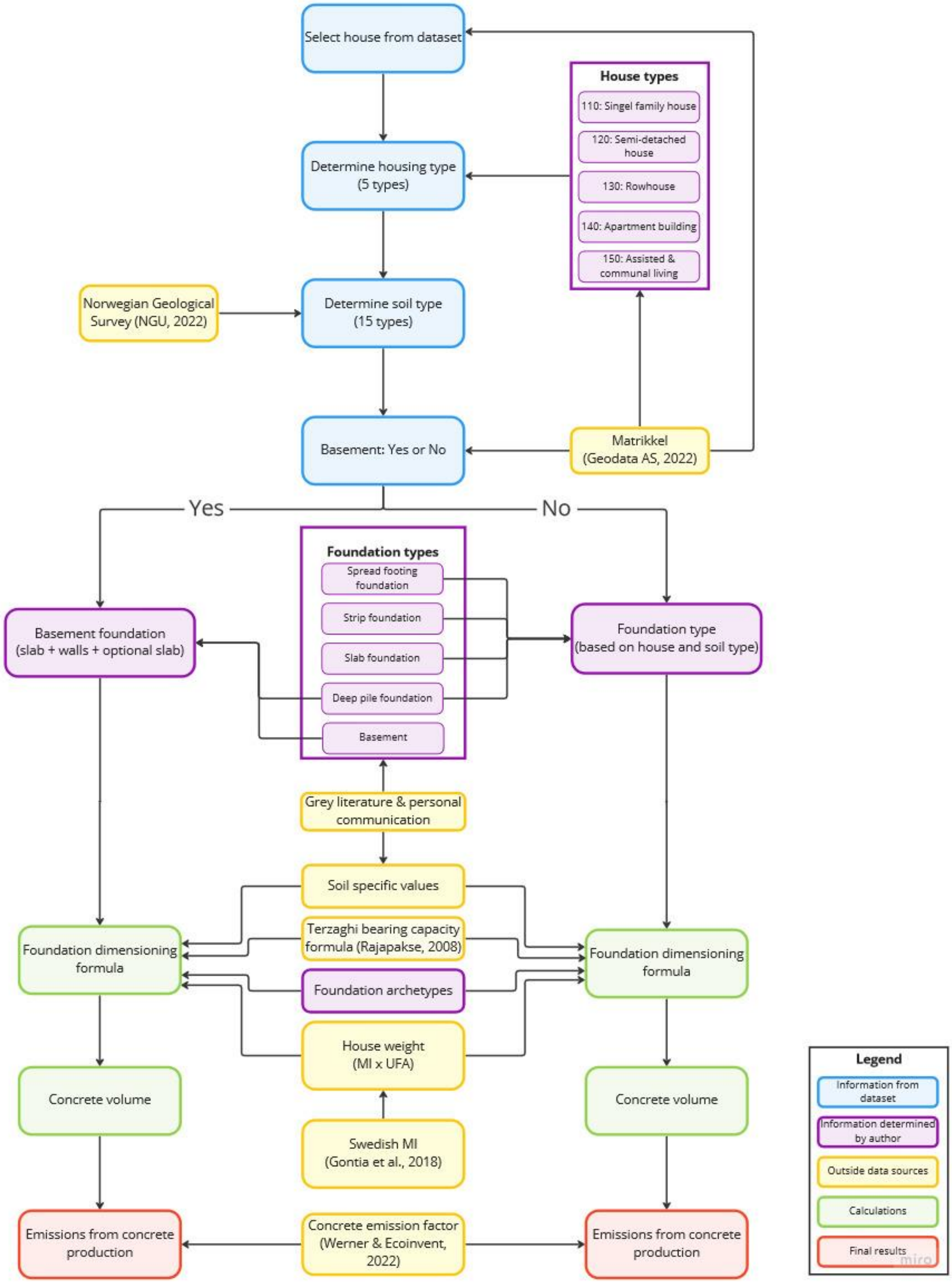


*Figure 4.2-3: Foundation model data flow.*

## *4.2.2 Transport Distance Model*

Lastly, information on the transport emissions is needed to 1) get a fuller picture of the cradle-to-construction site emissions from foundation building and 2) to compare the transport emissions to the production emissions. Ultimately, the model provides the road distance between each building and the four concrete mixing stations in Trondheim and selects the shortest route (see Figure 4.2-4). The model can be found in the Supporting Information.

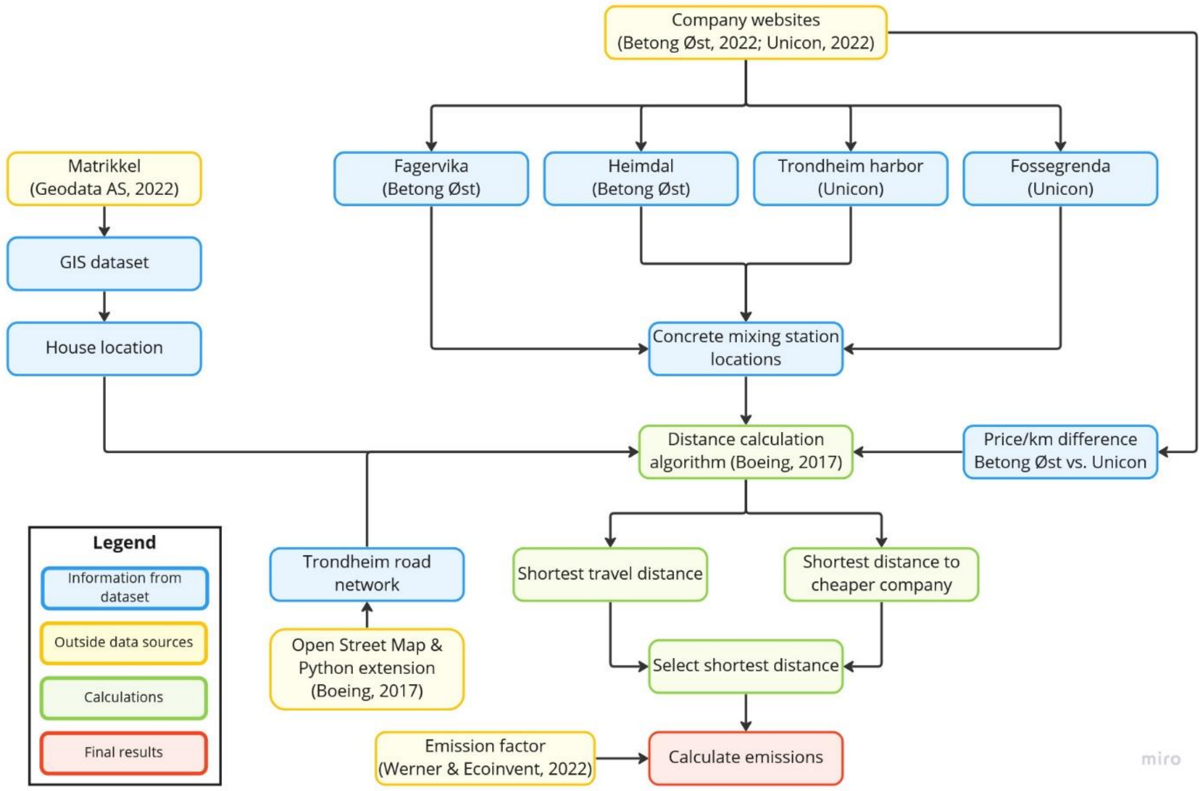


*Figure 4.2-4: Data flow overview of the transport distance model.*

#### 4.2.2.1 Data Requirements

The algorithm uses the Python library OSMnx from Boeing (2017), which provides the road network data and path finding algorithm. It downloads Trondheim's road network from the open-source map service Open Street Map (Boeing, 2017). Important to note is that Google maps offers the same service. Moreover, their service is more precise than the OSMnx algorithm. However, this is a paid service by Google and thus not usable for this project. After the road network is established, all relevant concrete mixing station locations are required. This data was obtained from the Norwegian Factory Concrete Association called FABEKO, whose members cover 95% of the Norwegian concrete market (FABEKO, 2022). The four locations were confirmed by checking the two owning companies' websites (Betong Øst, 2022; Unicon, 2022). Furthermore, their relevance for this thesis was verified by contacting the owning companies Betong Øst (M. Raaen, personal communication, 28.09.2022) and Unicon (K. Gustad Rønning, personal communication, 28.09.022) and by talking to a concrete truck driver at a construction site (anonymous, personal communication, 15.11.2022). Another important aspect is the price per $m^3$ of concrete. The two companies in Trondheim, Betong Øst and Unicon, sell at almost the same price of 1515 NOK and 1695 NOK respectively at the time of writing (November, 2022) (Betong Øst, 2022; Unicon, 2022). The price difference may cause cost-optimizing costumers to select one supplier over the other even if that means a longer transport distance. Based on the price per kilometer transported of both companies it was determined that Betong Øst costumers can be 2.5 kilometers further away until prices become the same. This was taken into account when selecting the likely delivery distance. The exact coordinates of the concrete mixing stations were taken from Google maps. The house location coordinates were determined in ArcGIS Pro, with the help of a feature to mid-point conversion. The point coordinates were extracted and fed into the algorithm. Lastly, a transport emission factor is required. This was taken from the Ecoinvent process *market for transport, freight, lorry 16-32 metric ton, EURO6*, in Europe (Valsasina

& Ecoinvent Centre, 2022). The European region was selected due to the absence of a specific Norwegian process. The capacity of 16 to 32 tonnes was selected, because an average concrete truck weighs up to 30-32 tonnes (Betong Øst, 2020; Betongsentrum.no, 2022).

#### 4.2.2.2 Data Processing

The transport distance algorithm takes the location of a house in the dataset and then calculates the transport distance to all four concrete mixing stations. It then takes the shortest distance, while considering the price difference of the two companies. One limitation of the Open Street Map road network and the OSMnx route finding algorithm is that distance can only be calculated between nodes (see Figure 4.2-5). This means that in some cases the transport distance is underestimated, while in other cases it may be overestimated. The scale of this can only be ascertained through extensive manual checking by typing in addresses in Google maps and comparing transport distances to the model results. This is not a feasible approach. Lastly, the transport distance and concrete volume required for each house is multiplied with the transport emission factor to attain the emissions from transport.

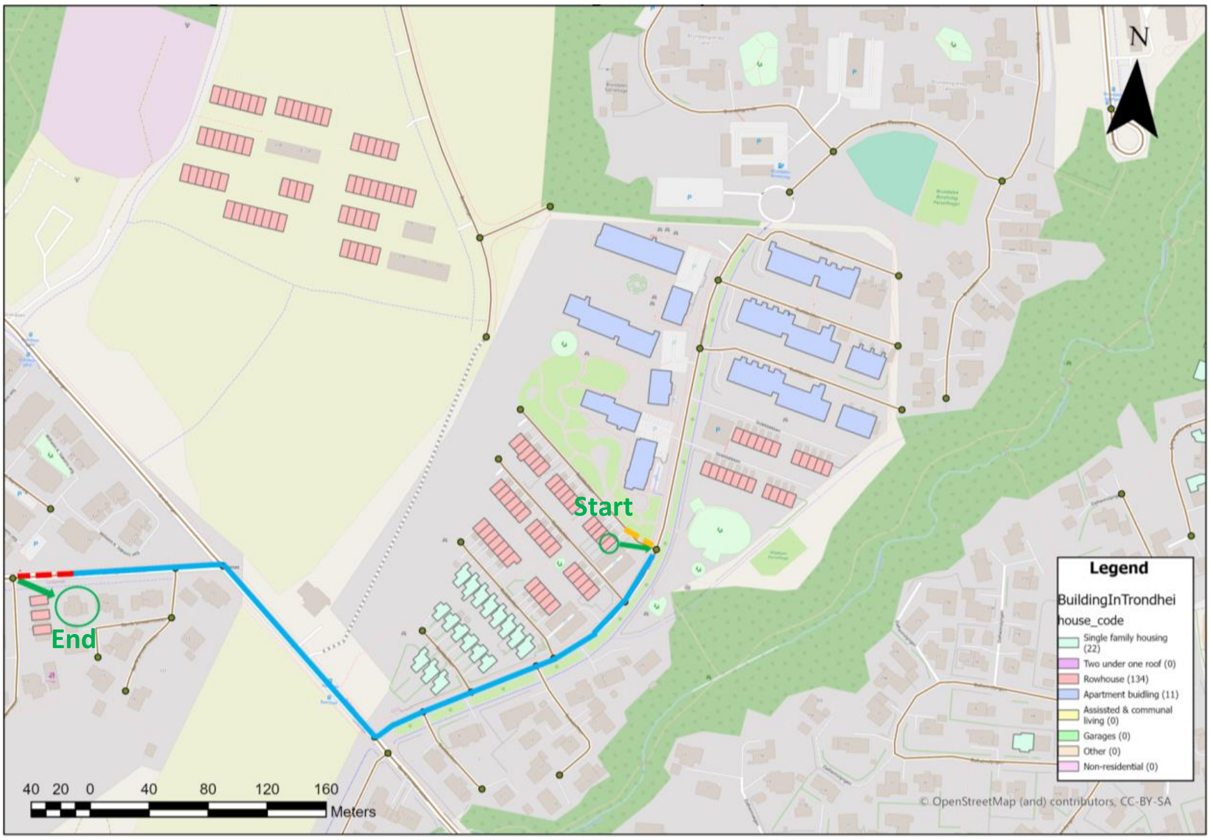


*Figure 4.2-5: Visualization of inaccuracies of path calculations. The blue + red path is calculated as total distance. However, the orange line at the start should be added, while the red line at the end should be disregarded. This is due to the node guided algorithm. For more on this check the OSMnx documentation online.*

# 5 Results

The next chapter reports the results. For clarity they are structured in five sections. Section 5.1 evaluates the material production and transport emissions. Section 5.2 presents the material distribution per neighborhood. Section 5.3 introduces the results of MI factors by building type and section 5.4 the MI factor by soil type. Section 5.5 elaborates on the MI factor results of houses with and houses without basements.

## 5.1 Material Production and Transport Emissions

The total material stock addition from residential building foundations built between 2010 and 2020 is about 507 000 tonnes. Figure 5.1-1 breaks down the material stock contributions per building type in all of Trondheim. About half (51%) of the added concrete was used in apartment building foundations. 21% of the concrete was used in single-family houses. Rowhouses used about 17% of the total concrete. Semi-detached houses and assisted & communal living used about 5% each.

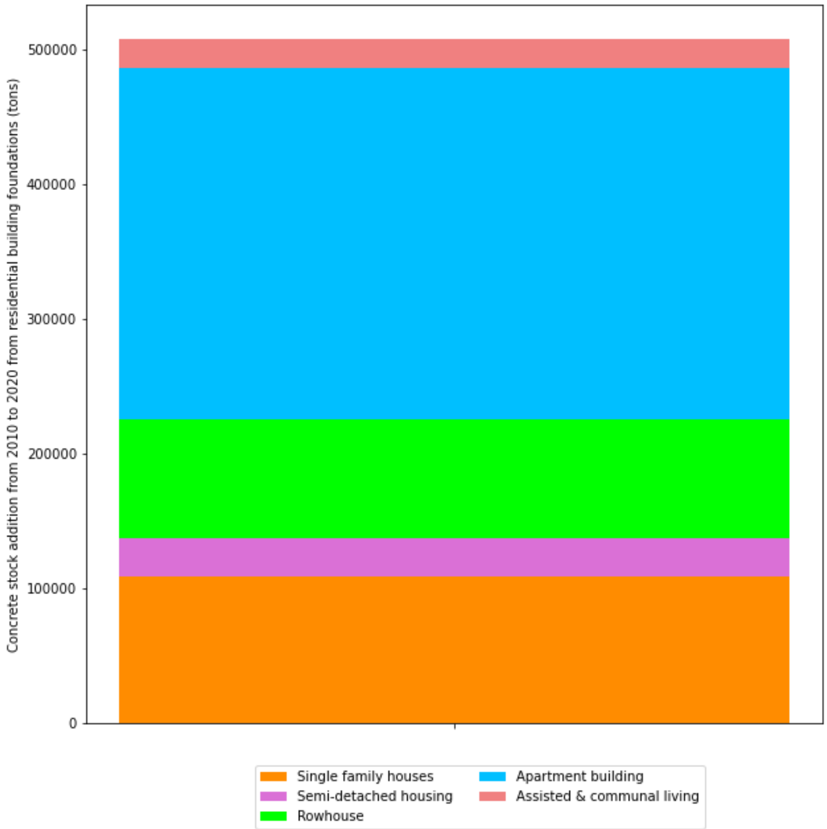


*Figure 5.1-1: Total concrete mass in building foundations added to the material stock between 2010 and 2020.*

The model results show that total concrete production emissions for residential building foundations far outweigh the last-leg concrete transport emissions (Figure 5.1-2). At an emission factor of 99 kg $CO_2$ eq./tonne concrete this results in about 50 000 tonnes of $CO_2$ eq. of emissions. The results indicate that one-way transportation by a 32-tonne diesel truck produced about 506 tonnes of $CO_2$ eq. On average, this means, that for each building 14 tonnes of $CO_2$ eq. were emitted for concrete production, while 0.14 tonnes of $CO_2$ eq. were emitted for transportation.

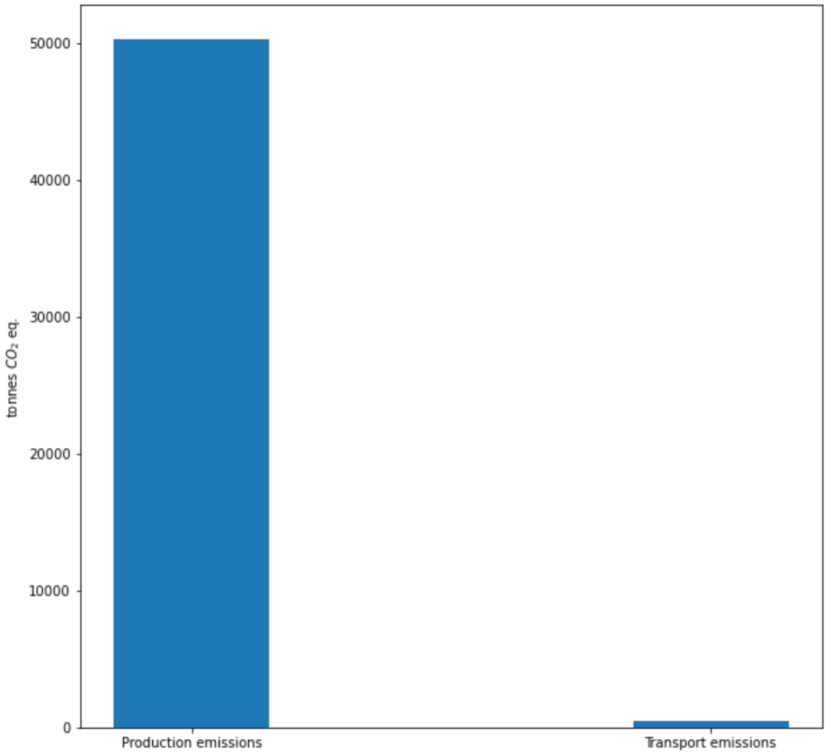


*Figure 5.1-2: Concrete production emissions vs. last-leg transportation emissions from concrete supplier to construction site.*

A comparison each housing type's share of overall production and last-leg transport emission shows that their shares are similar (Figure 5.1-3). The slightly higher transport emissions of single-family- and rowhouses compared to their share of production emissions can be explained with their higher average delivery distance compared to the other house types (Table 5-1). This is due to the fact that, especially single-family houses were the dominant building type in the outer neighborhoods of Trondheim (see Appendix C).

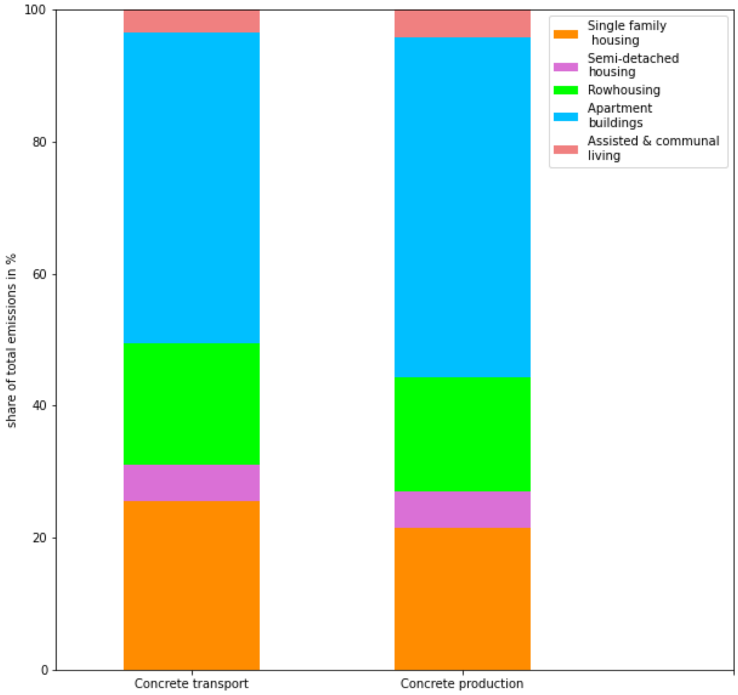


*Figure 5.1-3: Share of each house type's contribution to the total emissions of concrete transport and production. As transport emissions depend on transported mass and travel distance, a higher share of transport emissions than production emissions indicates that the transport distance was higher than for other housing types.*

*Table 5-1: Average concrete transportation distances by house type.*

| House type | Average delivery distance (km) |
|---|---|
| Single-family house | 6.5 |
| Semi-detached house | 5.4 |
| Rowhouse | 5.6 |
| Apartment building | 4.8 |
| Assisted & communal living | 4.2 |

## 5.2 Material Distribution per Neighborhood

While the total of materials used provides the addition to the material stock of concrete in Trondheim's building foundations, its geospatial explicitness provides a better understanding of the locations where it can be found. Trondheim's neighborhoods vary in size and in construction activity and thus newly material added to the stock. Figure 5.2-1 shows the newly added housing over the last 10 years measured in $m^2$ UFA and the concrete material stock additions from 2010 to 2020 from the foundation construction of residential buildings. The more material was added to the stock, the darker the blue. Most additions took place in the neighborhoods of Heimdal, Tiller-Hårstad and Byåsen, as can be seen by the darker shades of blue. The addition of UFA as an indicator of construction activity in a neighborhood is shown as a green bar. The higher the bar the more floor area was built in a neighborhood, thus the more construction activity took place. For an overview of the building types added in each neighborhood see Appendix C. Looking at Figure 5.2-1, the highest material stock addition took place in Heimdal, yet the neighborhood only added the second most UFA. The most UFA was added by the northern neighborhood Charlottenlund-Jakobsli. This disparity between the added UFA and the added material stock becomes even more interesting in the southern-most neighborhood, Klæbu. The neighborhood ranks 6th among the highest material stock additions, while only having added the 16th most UFA. This suggests that the material inputs per neighborhood differ. This results in strongly differing MI factors per neighborhoods, which is illustrated in Figure 5.2-2. In fact, Tiller-Hårstad and Klæbu have the highest MI factors. This means both neighborhoods require a lot of concrete in their foundations for a comparatively low amount of UFA added when comparing it to the other neighborhoods. The question is, why are the MI factors different across the neighborhoods?

The model contains two factors that influence the concrete requirement of a building. The first factor is the building type. Smaller buildings can be built with so-called shallow foundations that do not require much material. Larger buildings, such as apartment buildings and assisted & communal housing require deeper foundations to provide enough stability and thus more material. The second factor is the soil type. If a small building is constructed on a soil type with less bearing capacity, then this also affects the foundation type, for example by requiring a deep foundation. The following sections analyze whether the MI factor depends on the building type or the soil type.

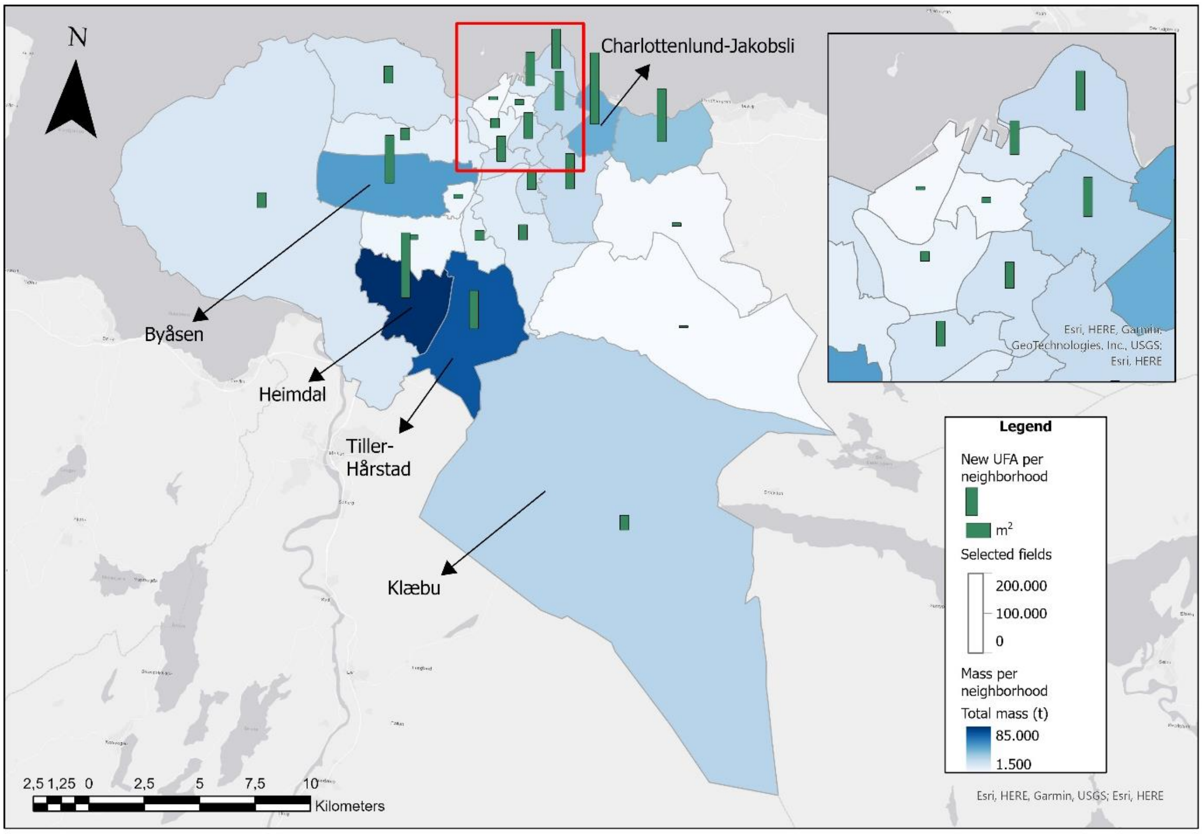


*Figure 5.2-1: Concrete mass (blue; the darker the more) and new UFA (green, the higher the bar the more) added per neighborhood between 2010 and 2020.*

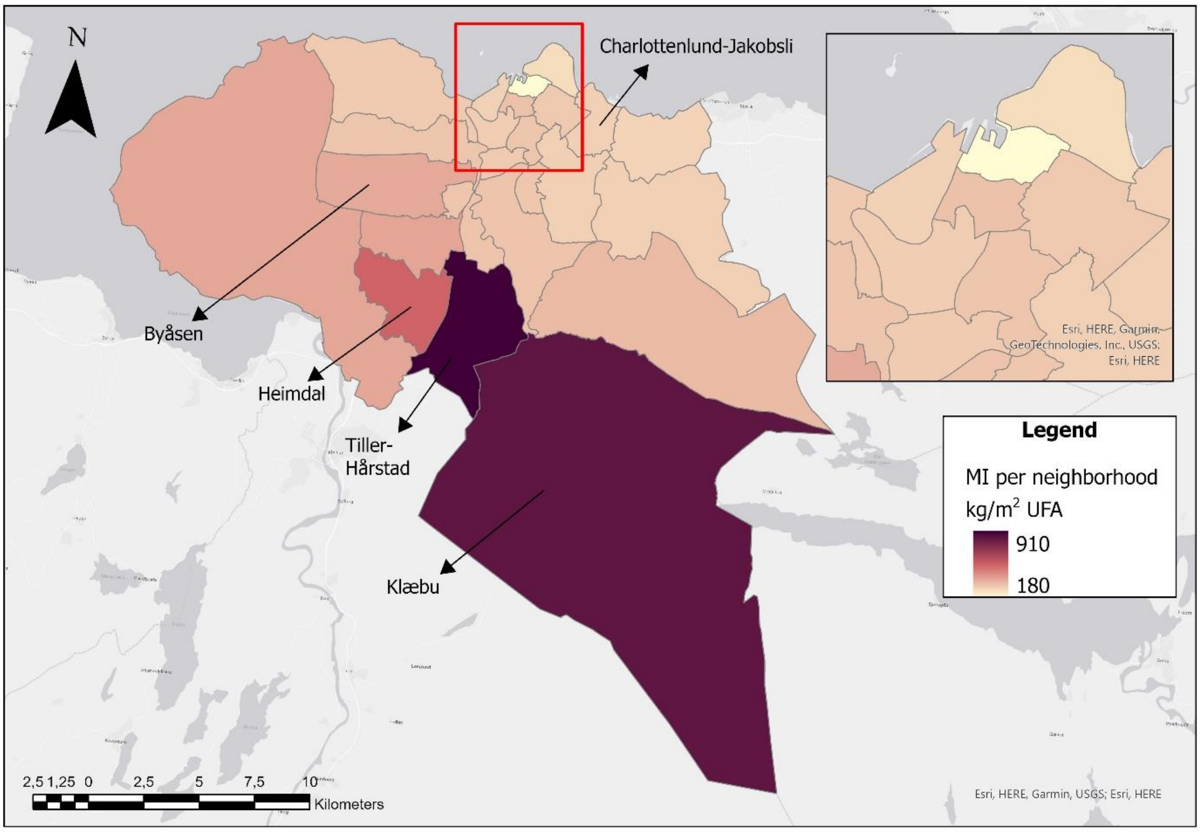


*Figure 5.2-2: MI factors (red; the darker the higher) per neighborhood between 2010 and 2020.*

## 5.3 Material Intensity Factors by Building Type

Across all building types, the average MI factor is 402 kg concrete/m$^2$ UFA. Figure 5.3-1 shows the average material intensity factors disaggregated by building type. It shows that the MI factor does not vary considerably between building types. Rowhouses have the highest MI factor at 484 kg concrete/m$^2$ UFA, meaning it lies about 20% above the average. Apartment buildings have the lowest MI factor with 355 kg concrete/m$^2$ UFA, lying about 11% below the average. While the 20% higher material use of rowhouses may seem considerable, this only amounts to 0.03 m$^3$, so not a substantial amount.

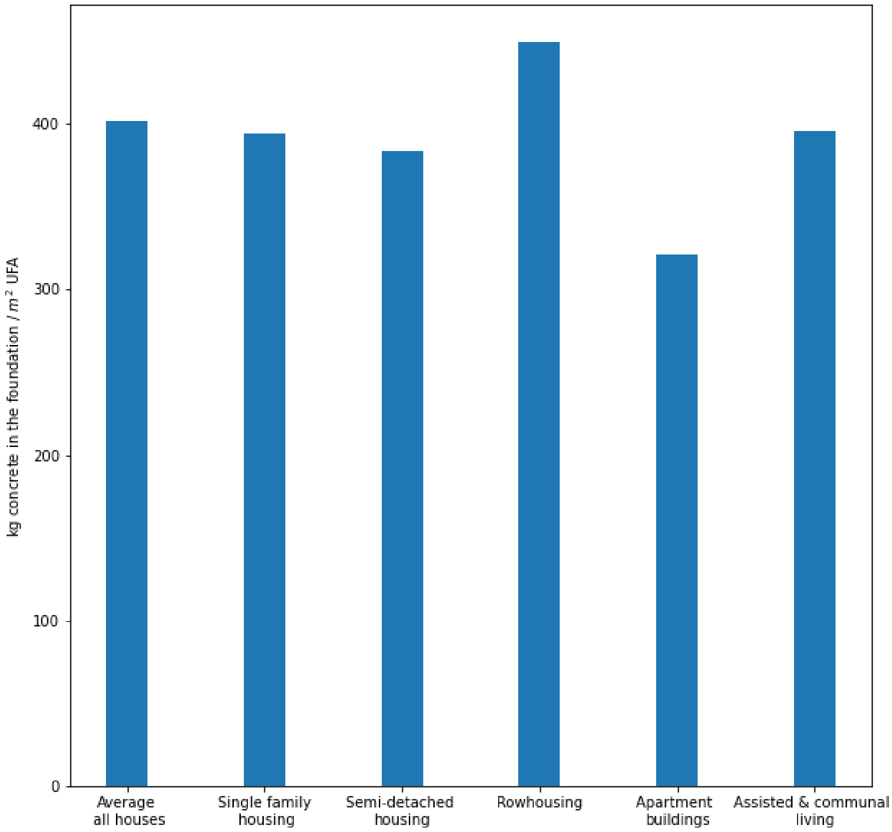


*Figure 5.3-1: Average MI factors per building type.*

Interesting to note is that when looking at the distribution of MI factors in a histogram, there is an accumulation around a MI factor of 300 kg concrete/m$^2$ UFA and 1500 kg concrete/m$^2$ UFA (see Figure 5.3-2). However, in both accumulations rowhouses and single-family houses are dominant, which suggests that the building type is not the driving factor behind the high MI factors of Tiller-Hårstad and Klæbu (see Figure 5.2-2).

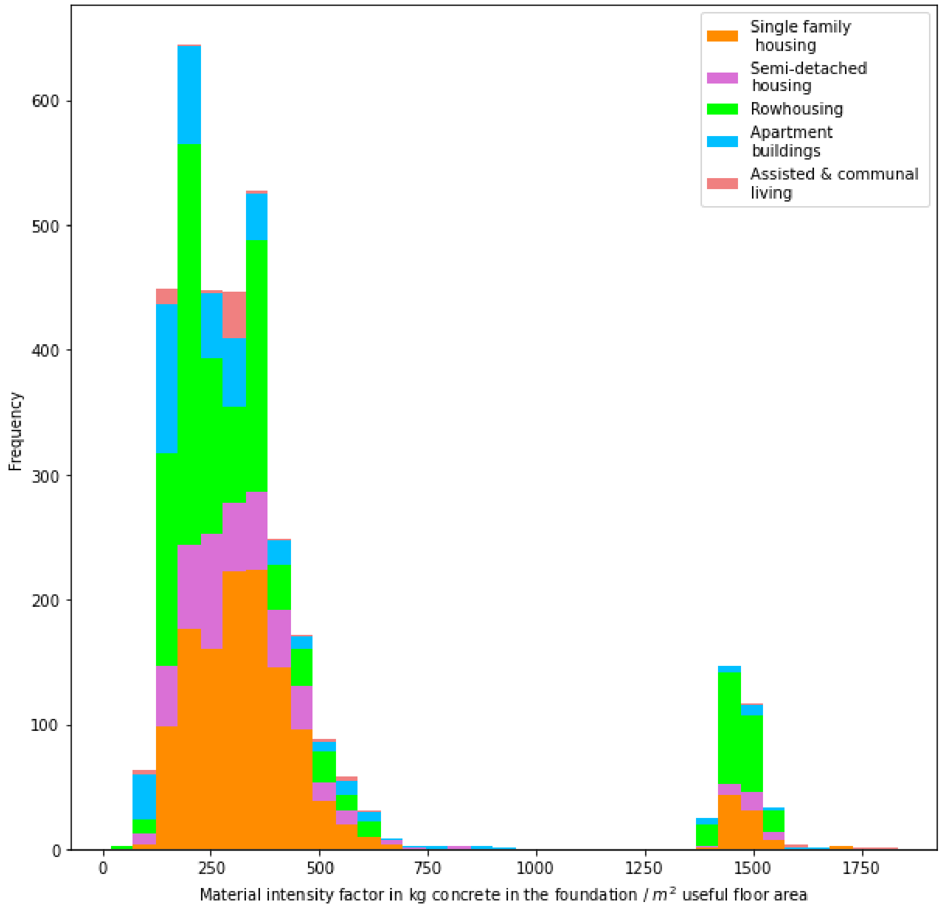


*Figure 5.3-2: Histogram of the material intensity factor distribtion across the dataset disaggregated by house type.*

This conclusion is further supported when looking at a distribution of the building types built in some relevant neighborhoods. The selection is based on their relationship of their added floor area and their MI factor. The neighborhood Jakobsli was selected, because it has the highest amount of UFA added (179198 m$^2$), but a MI factor on the lower range (284 kg concrete/m$^2$ UFA). Byåsen was selected, because it added a considerable amount of UFA (119845 m$^2$) but had a lower-mid ranging MI factor (371 kg concrete/m$^2$ UFA). Heimdal added lots of housing (163361 m$^2$) but has the third highest MI factor (539 kg concrete/m$^2$ UFA). Tiller-Hårstad and Klæbu have the highest MI factors (912 kg concrete/m$^2$ UFA and 835 kg concrete/m$^2$ UFA, respectively), yet low added UFA (96069 m$^2$ and 36668 m$^2$, respectively). Figure 5.3-3 shows this distribution. It becomes apparent that rowhouses seem to be the dominant building type added in each neighborhood. However, there appears to be no correlation between the share of row housing in a neighborhood and its MI factor. This lack of correlation applies to the distribution of the other housing types as well.

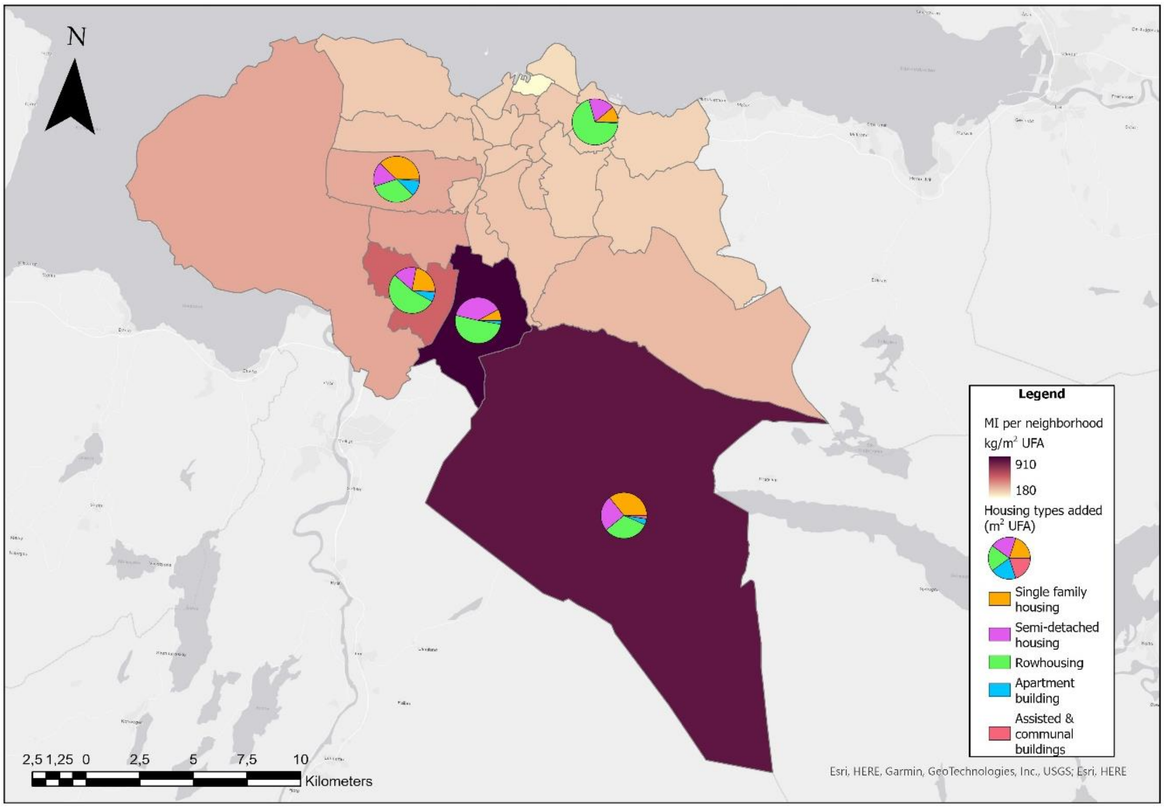


*Figure 5.3-3: MI factors (red; the darker the higher) and share of housing types (pie charts) as part of the total new useful floor area added between 2010 and 2020 per relevant neighborhood.*

## 5.4 Material Intensity Factors by Soil Type

The other factor that affects the material requirement of the foundation is the soil type. Figure 5.4-1 shows that buildings constructed on peat and bog soils require significantly more material per m$^2$ UFA than buildings constructed on any other soil type that can be found in Trondheim. This suggests that the soil type may indeed be the driving factor behind the MI factor. This is supported when looking at Figure 5.4-2. It shows the soil type shares across the relevant neighborhoods. Indeed, the share of peat and bog soils (pink) correlates with the neighborhoods that have high MI factors.

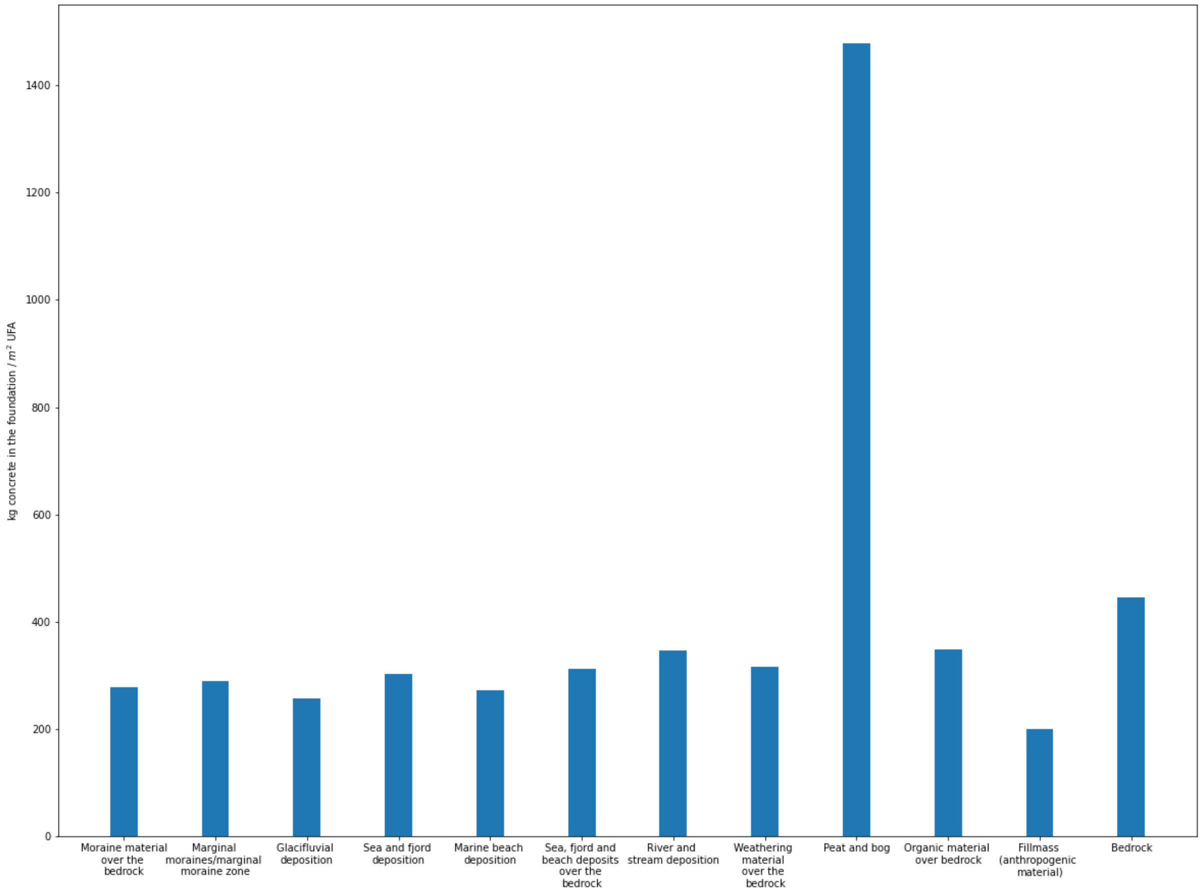


*Figure 5.4-1: MI factors per soil type.*

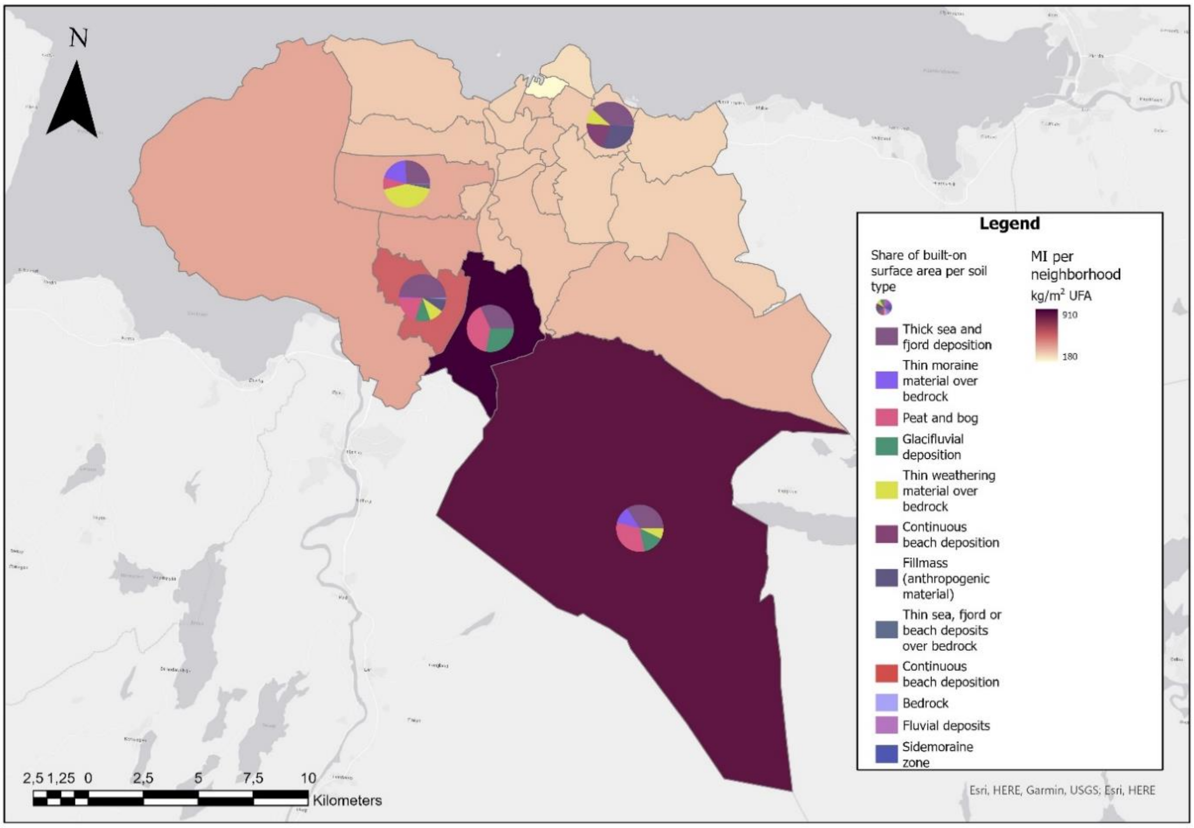


*Figure 5.4-2: MI factors (red; the darker the higher) and shares of built-on soil types (pie charts) in relevant neighborhoods. Soil type share shows constitution of built-on grounds.*

## 5.5 Houses With vs. Houses Without a Basement

The municipality of Trondheim was furthermore interested in the difference of material input between buildings that have a basement compared to buildings that do not. The results in Figure 5.5-1 indicate that there is a difference between the MI factor of buildings with a basement versus buildings without a basement. The difference between the two building types is 103 kg concrete/m$^2$ UFA, which means buildings with a basement use about 22% more material, corresponding to about 0.04 m$^3$. Figure 5.5-2 shows the distribution of building types with and buildings without a basement. The number of buildings instead of UFA was purposefully selected to visualize what building type tends to have a basement. The above-ground structure, the UFA, is not necessary and would actually skew the results towards apartment buildings due to their size. The figure shows that single-family and semi-detached housing as well as apartment buildings are more likely to have a basement or underetasje than not. Row housing, conversely, has a higher share of buildings without a basement. Assisted and communal living is more or less split even between the buildings with and without a basement.

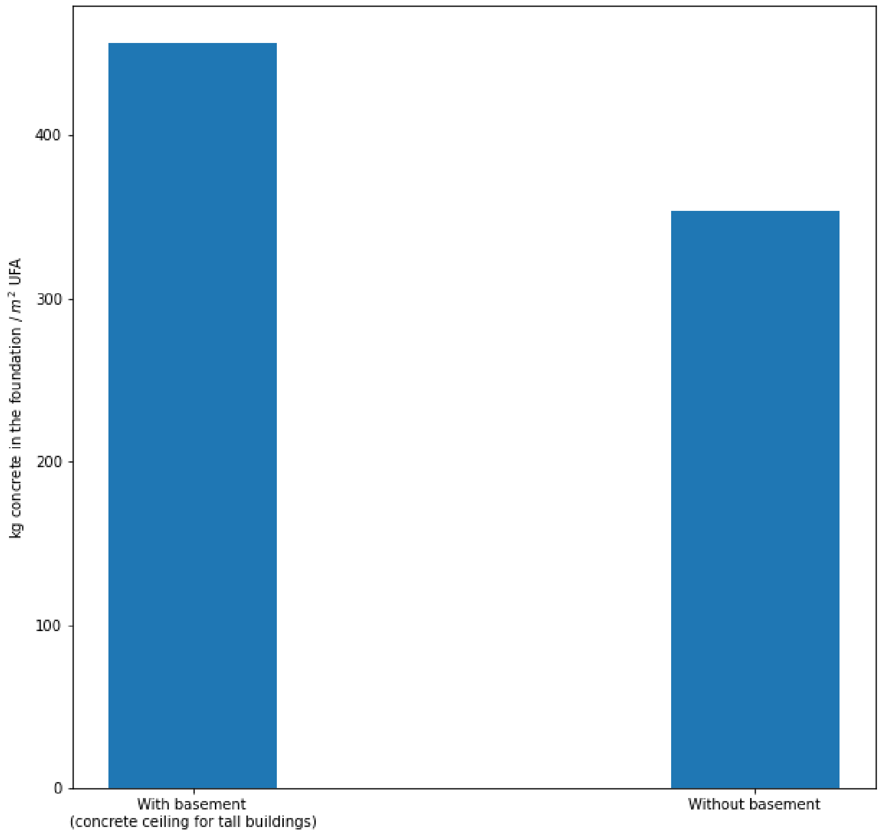


*Figure 5.5-1: Average MI factor of buildings with a basement versus buildings without a basement.*

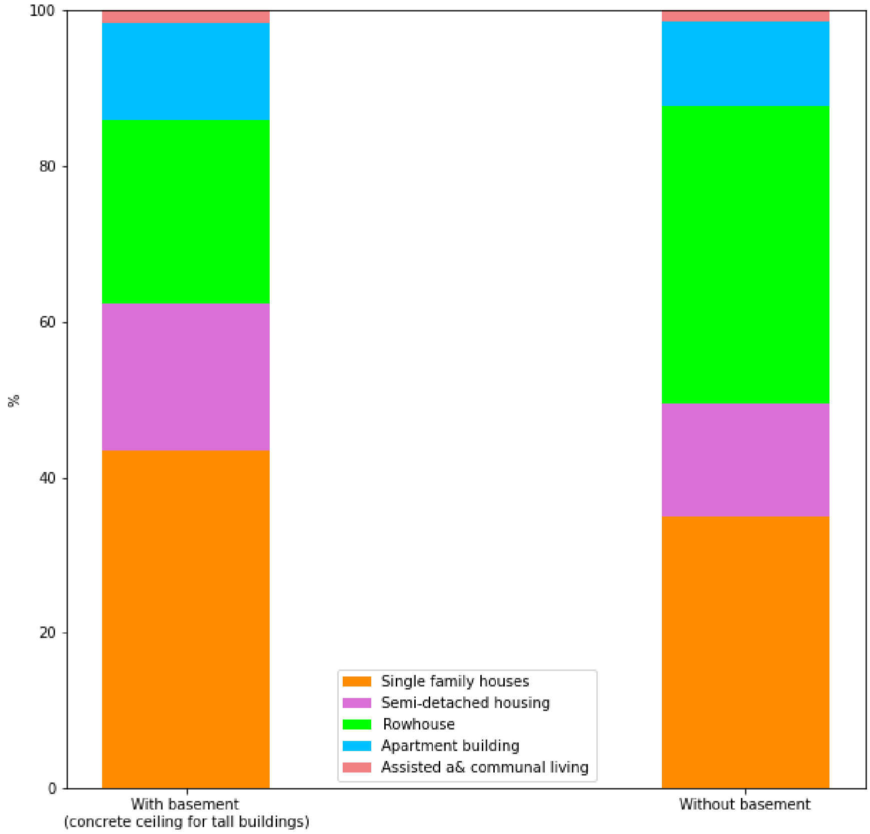


*Figure 5.5-2: Share of each building type from the total number of houses with (left) and without (right) basement. Rowhouses are the only building type where not having a basement is more common.*

# 6 Discussion

The discussion evaluates the results and places them in their greater context. Here special attention was given to linking insights to academic as well as city planning purposes.

## 6.1 Transport Emissions

In Trondheim, the average distance between a housing construction site and its nearest concrete mixing station is 5.7 km during the modelled time period. One concrete supplier offers the first 6 km of transportation free of charge, for every additional km the costumer needs to pay extra (Unicon, 2022). This indicates that either 1) the market situation forces the supplier to offer concrete only in a 6 km radius or 2) the supplier chose to limit themselves due to other factors. In any case, this shows a preference of suppliers to supply within a 6 km radius, thus an average of 5.7 km transport distance is very close to this supplier preference. This provides two insights. First, the locations of concrete mixing stations were well placed for the construction projects that took place in the last 10 years. Second, further optimization through relocation to minimize transport distances is not viable, because 1) the transport distance is already short and 2) the areas which need to be supplied with concrete are already well covered by the existing deliver stations.

Because the last-leg transport emissions are equivalent to 1% of the total emissions, they will not be further explored in this thesis for three reasons. First, any achievements in reducing transport emissions are negligible, because they contribute only 1% to total emissions. Second, the delivery distances are already very short and thus further optimization is unlikely. Third, this means that further emission reductions can most likely be achieved by changing the transport technology, for example by using other fuels. This goes beyond the scope of this thesis. As a result, the following discussion will focus on the material requirements of foundations, its connected emissions and how these can be mitigated.

## 6.2 Building Types

The MIs per building type show no considerable difference between the different building types. This means that no building type foundation is more materially efficient than the others. The reason for the MIs being similar across the building types is the relationship between building weight and UFA.

Small buildings have little UFA; thus, they weigh little. Therefore, they need less material in their foundation. When calculating their MI factor, a small foundation value is divided by a small UFA value. Large buildings, on the other hand, have lots of UFA, thus they weigh a lot more. Therefore, they require more material in their foundation. When calculating their MI factor, a large foundation value is divided by a large UFA value. The MI factor is a ratio, and the results indicate that the ratio of concrete in the foundation to the amount of UFA is the same for small buildings as for large buildings. The above steps to the conclusion are visualized in Figure 6.2-1 below.

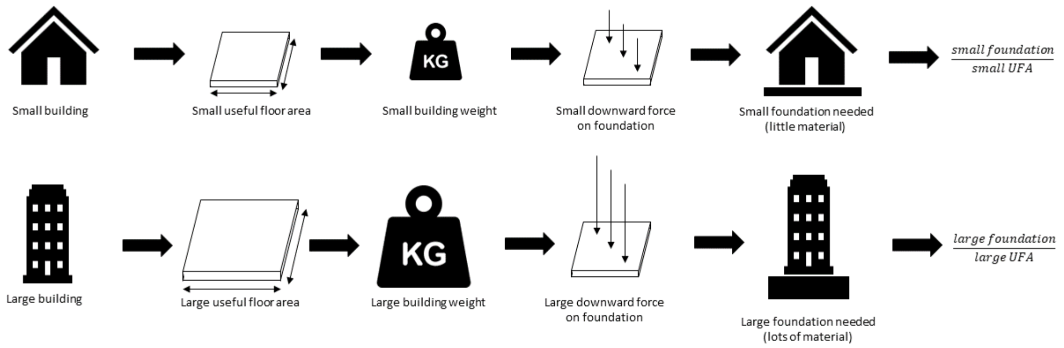


*Figure 6.2-1: Explanation why the MI factor for small buildings is similar as the one to large buildings. The reason is that the MI factor is a ratio, rather than an absolute value.*

A similar trend shows when comparing the MIs of buildings with basements to buildings without basements. The minimal difference between the two MI factors means that there is no foundation type that is clearly more materially efficient than the other. The reason for an only small increase in MI is connected to the increase in material needs, yet also the simultaneous increase in UFA. As a basement foundation provides good stability it only requires concrete for a basement slab, load bearing walls and a ceiling. When comparing a basement foundation with a non-basement foundation, the additional material requirements thus stem from the extra walls needed and potentially the ceiling. This increases the total mass in the foundation. However, the basement's additional UFA also increases the building's total UFA. Therefore, the MI factor of building foundations with a basement is only slightly higher than that of buildings without a basement, because the material use increase is compensated by the UFA increase. Interestingly, two structural engineering professors from NTNU both, independently, stressed the value of basements (Dr. A. M. Selberg, personal communication, 1.12.2022; Dr. T. Kanstad, personal communication, 5.12.2022). Their two main arguments were 1) the natural stability provided through the structure under ground and 2) the additional UFA gained without increasing the building footprint or height. This argument becomes likely viable if municipalities lack space. For Trondheim this is not the case. However, future research could explore the tradeoffs of building a basement versus building a storage shed or an additional floor in a building.

## 6.3 Soil Types

The results show that considerably more concrete for the foundation is needed per $m^2$ UFA when building on peat and bog soils than when building on any other soil type in Trondheim. This means that one should avoid building on peat and bog if the goal is to reduce material use and thus emissions. The higher material requirements on peat and bog are due to the fact that this soil is considered to have no bearing capacity, mostly because of its high water and organic soil content (Cao et al., 2021; Munro, 2005). This leads to high compressibility and low strength of the soil. As a result, it cannot support any building weight. Therefore, foundations need to be constructed that either 1) pass through the soil layer until they reach another soil layer that has a higher bearing capacity or 2) until the friction along the foundation piles is sufficient to hold the building on its own. To achieve this, deep foundation piles are needed. Figure 6.3-1 shows a peat and bog area in the neighborhood of Tiller-Hårstad in Trondheim in February 2023. To reiterate from the methodology, I assumed the use of end-bearing piles, each weighing about 9.4 tonnes. As these are the foundation structure that bear the entire building, a lot of these piles are needed to support the structure. This drives up the material requirements on peat and bog soils.

*Figure 6.3-1: Photo of frozen peat and bog soil in Tiller-Hårstad. Once it gets warmer the ice melts and the soils become swampy again. (Picture taken by the author, February 2023)*

All other soils in Trondheim, on the other hand, have higher bearing capacities. Because the soil types across the municipality are all similar, ranging from bedrock to sandy rocks, their bearing capacities are also similar. As a result, they all have similar MI factors. The higher bearing capacities greatly reduce the material need in the foundations, because the soils are able to take up the load better than peat and bog. Additionally, more stable soil types allow the use of shallow foundations for smaller buildings. These require less material as they do not reach as far into the ground as deep pile foundations.

All in all, this leads to an 80% increase of concrete in the foundation when building on peat and bog compared to building on the other soils. This brings about a major insight: substantial amounts of concrete can be saved if one avoids building on peat and bog. This would reduce emissions considerably, because concrete is so emission intensive in its production.

There are a few avenues for further research on this. First of all, it would be interesting to explore if there are any foundations that are less resource intensive than deep pile foundations that could also provide sufficient support. Moreover, more soil types should be explored. My analysis is very regionally specific and only treats soil types that are present in Trondheim. By expanding the model to other locations more soil types could be included. It would be interesting to see if there are other soil types, besides peat and bog, that require extensive material inputs when building a foundation on them. A possible indicator for such soil types could be 1) low bearing capacity of the soil type or 2) the need for deep pile foundations on a soil type.

## 6.4 Comparison to Earlier Publications

When only looking at foundation material requirements, it seems most efficient to construct buildings with a small footprint on the ground, but tall, e.g., apartment buildings. That way the increasing number of UFA or households share the material needs of the foundation. As the building height increases so does the building weight. This causes an increased demand of material in the foundation. However, this material need increase in the foundation seems to be outweighed by the increase in UFA or households. To situate these insights on foundations in the greater context, however, I will now compare my results to previously done research.

In their paper Gontia et al. (2018) attribute a share of foundational structure and above-ground structure to each of their proposed MI factors. The above-ground share was used by my model to estimate each building's weight. It is thus possible to explore the building's entire weight by adding my calculated foundation weight to the estimated building weight. Figure 6.4-1 shows my model results. For the smaller buildings the foundation typically accounts for about 70% of the total building weight. For the larger buildings the foundation accounts for about 30% of the total building weight. These findings are insightful for two reasons.

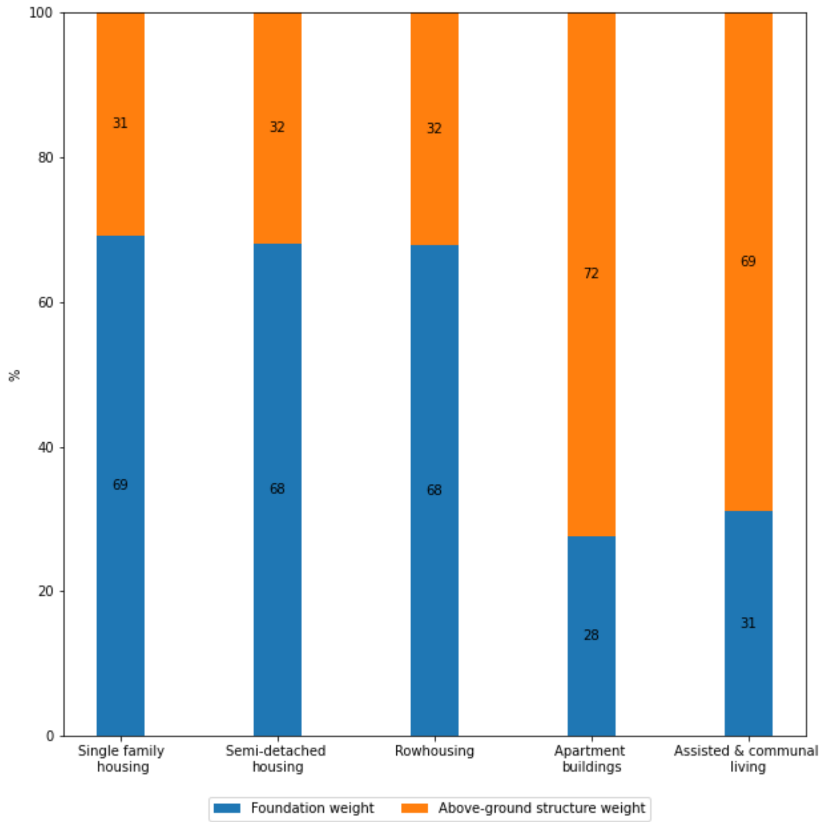


*Figure 6.4-1: Average mass distribution between foundation and the above-ground structure per building type from my model.*

First, they align with the results by Gontia et al. (2018) as they stated that small building foundations account for about 60% of the building weight, while for large buildings the foundation accounts for about 25%. One could believe that, because my model used the MI factors by Gontia et al. (2018) to calculate the building weight, that this could cause the similarity in results. This is not the case, because my model calculated the foundation dimensions and thus the weight of the foundation for each given building weight in combination with the soil type and foundation type. Thus, the distribution between building weight and foundation weight was determined independently from Gontia et al. (2018). Moreover, Arceo et al. (2023) find that the foundation of single-family houses in

Toronto, Canada makes up about 69% of the total building mass. The similarity in mass distributions corroborates the results of both Gontia et al. (2018) and Arceo et al. (2023), as well as mine. Moreover, this indicates that the assumptions in my model were realistic. In a sense my model is being validated against the real case studies performed by Gontia et al. (2018) and Arceo et al. (2023). This is summarized in Table 6-1.

*Table 6-1: Comparison of my mass distribution results to other papers. Mass distribution is split by above-ground structure and foundational structure and by two house types: 1) single-family housing and 2) multi-family housing.*

| Source | Single-family housing | | Multi-family housing | |
|---|---|---|---|---|
| | Above-ground mass share | Foundation mass share | Above-ground mass share | Foundation mass share |
| Gontia et al. (2018) | 40% | 60% | 75% | 25% |
| Arceo et al. (2023) | 31% | 69% | - | - |
| My results | 32% | 68% | 70% | 30% |

Two important insights come from this confirmation of mass distribution among building types. First, substantial material savings can be achieved when constructing small buildings by optimizing the foundation. The share of mass distribution amongst smaller buildings has shown that a majority of the mass is in the foundation. This means that any successful reductions of foundation mass will result in a substantial reduction of overall material mass requirements of the building. This will reduce the emissions from building construction twofold. First, less material will be needed. Especially concrete savings will cause a considerable reduction in emissions of the building because its production is emission intensive. Second, any reductions in mass requirements of the building result in reduced need for transportation, thus also avoiding transport emissions. In reality, however, foundations are often already optimized for minimal material use to minimize material costs. As a result, further research into how material savings in small building foundations can be achieved is needed, for example by exploring alternative foundation materials to concrete.

The second insight is that in large buildings the foundation represents a smaller share of the total building mass. This means that any strategies to reduce material use in these foundations will only minimally reduce the overall material requirements. Therefore, a focus on the above-ground structure is advisable. An interesting material that has been used in various apartment building projects over the past years is wood. This material is an active carbon sink and has reduced weight compared to concrete or brick bearing structures. As a result, it also reduces the above-ground structure's total weight, thus reducing the stress on the foundation and with that the foundation's material need. Further research into the reduction on above-ground structure weight could thus contribute to reducing the material need of large building foundations.

Lastly, Gontia et al. (2018) state that foundations are a dormant stock, so often not available for reuse. This is based on Tanikawa and Hashimoto (2009) who stated that foundations are sometimes left in the ground and might thus qualify as missing or dissipated stock. The distribution of mass in the five building types I investigated has shown that especially in small buildings the foundation makes up a very large part of the houses total mass. Including the foundation when planning reuse and circular economy policies, especially of smaller houses, could therefore increase the stock from which to draw from considerably. Thus, foundations should become part of the stock considerations when planning circular economies, because only then potential reuse options for the foundations will be considered. Moreover, this will help balance material in- and outflows in urban metabolism research (Tanikawa & Hashimoto, 2009).

## 6.5 Municipal Use of the Insights

### *6.5.1 Emission Hotspot: Concrete Production*

The emission hotspot of concrete use in residential building foundations is the concrete production. The main driver of these production emissions is the cement (Davis et al., 2018; Lehne & Preston, 2018). This is important to know for the municipality, because cement is not produced in Trondheim. Therefore, they have little influence over how the cement is produced. In fact, there are only two cement factories in Norway (Heidelberg Cement Group, 2022). All other cement is imported from other countries (Dr. Broekmans, personal communication, 07.09.2022; Worldbank, 2023). Even if the municipality could influence cement producers, the process itself is simply very emission intensive (Norcem, 2022). Another strategy to mitigate emissions from production, however, is to reduce production. Production reduces as demand reduces. As a result, I recommend the municipality to investigate potential policies that could reduce concrete demand in the city. One such strategy is soil-conscious zoning.

### *6.5.2 Municipal Plans and Future Zoning Strategies*

At the time of writing the Trondheim municipality is engaged in the planning process of the residential zones from 2022 to 2034. Thus, the insights from the following analysis may be directly useful for incorporation in the planning process. There are two types of residential areas under consideration called building zone type 1 and type 2. Type 1 building zones are designated city or district center zones, while type 2 zones are the surrounding housing areas around the center (Trondheim Municipality, 2022). Each zone type comes with specific requirements such as the allowed share of shops, what kind of shops, etc. Both zones, however, emphasize residential buildings, so they are the relevant plans to analyze.

Figure 6.5-1 shows the peat and bog areas (light brown) in Trondheim and the currently proposed building zones 1 and 2 in orange and yellow. Marked in red are the sections of the proposed building zones that are on peat and bog soils. This was determined by plotting the proposed building zones and the soil map used in the foundation model and calculating the overlap. Looking at the map, it becomes clear that the overlap is limited to a few areas in the south of the municipality. The total new zoning area is 14 km$^2$. Of that 0.7 km$^2$ overlap with peat and bog. That is around 5%. This overlap does not seem too large at first. However, since the average MI per m$^2$ UFA is 80% higher on peat and bog soils there is still a considerable potential to reduce material use and thus avoid emissions if the city decides to not build on these areas. Additionally, peat and bog soils are large carbon sinks who are believed can hold up to 5000 tonnes of carbon per hectare (10 000 m$^2$) (Oksholen, 2006). Thus, these 0.7 km$^2$ of overlapping zoning area could hold up to 380 000 tonnes of carbon, which could be released as construction on the peat and bog soil takes place. This could potentially add a considerable number of emissions on top of the emissions from increased material requirements. As a result, I recommend that a changing, or at least a discussion, of the zoning plans should be considered. This is especially useful now, because the proposed zoning is not yet final.

The insight on the importance of soil types for residential construction and zoning are twofold. First, Figure 6.5-1 shows that the location of peat and bog is known around the municipality. Thus, especially long-term expansion plans of the city should be made considering the presence of peat and bog areas. City planners can adapt the use of these areas by planning at most light-weight construction or small parks with construction limited to walkways and paths. These could be accessible to nearby inhabitants as a local recreation area. As the city may grow around these areas, this would also contribute to a greening of the city. It may even have effects on the local climate, like reducing the heat island effect of cities, though researching this goes beyond the scope of this thesis. Other considerations like potential ecosystem services of peat and bog areas and their value to local biodiversity should also be considered. All in all, I recommend city planners to take natural circumstances into account and investigate their potential advantages for the city.

Second, residential zoning types could be adapted to incorporate soil types and the soils' properties. Currently residential zoning types 1 and 2 specify the cityscape by determining the kinds of buildings and commercial activity within their zones. I suggest that more types of residential zones could be developed that are dependent on soil types. This means that, for example, special zoning types are created for peat and bog areas. These zoning types regulate that no heavy buildings are constructed in these areas to avoid overly use of materials for the foundation. By creating zoning types that are specific to peat and bog these areas become highlighted in future city plans. This allows for the easier planning of residential, commercial, and industrial zones around these areas, because they can be organically included in the surrounding zones. This is especially relevant as peat and bog soils cover around 9% of all of Norway's land area (Long et al., 2022).

More specific recommendations go beyond the scope of this thesis. Thus, further research should determine what cities require and what fits best to utilize peat and bog areas to ensure that the material use is as low as possible. Moreover, further exploration of city planning around peat and bog areas should be conducted. There may be tradeoffs where the increased material requirements of building on peat and bog are justified, because emission reductions can be achieved in other domains, for example transport.

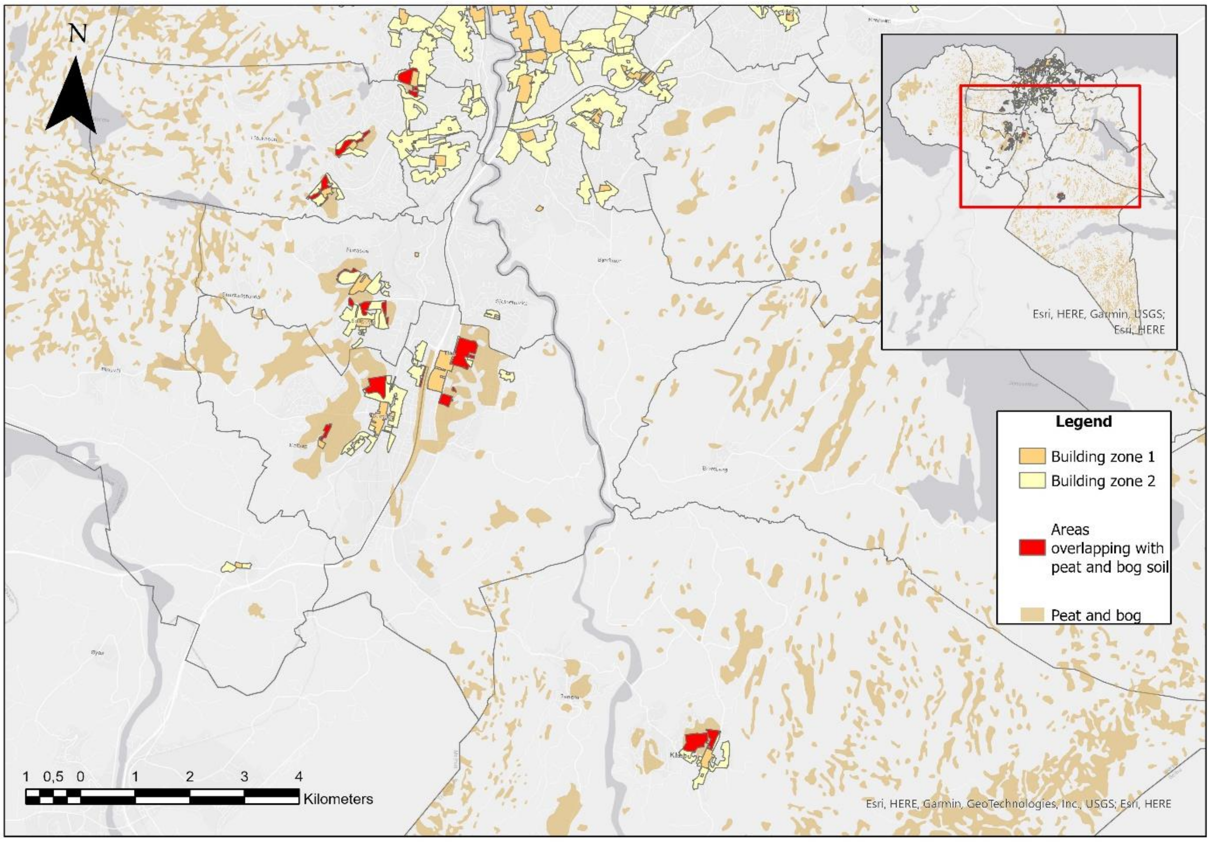


*Figure 6.5-1: Planned residential zones marked in yellow and orange. Planned residential zones overlapping with peat and bog soils marked in red. The surrounding peat and bog soils in the area are marked in light brown. Zoning data from the municipal worker H. Strand (personal communication, 10.01.2023). Soil data from NGU (2022).*

## 6.6 The Question of the Reference Unit

Material efficiency is always related to a reference unit. This reference unit is selected based on the good or service that is being assessed. As the reference unit changes so do the results on material efficiency (Arceo et al., 2023). When wondering what the most materially efficient building type is, the answer is: It depends. Arceo et al. (2023), compared single-family houses' material requirements per 1) one $m^2$ floor area, 2) one complete building and 3) one bedroom. The buildings which were deemed most materially efficient changed depending on the reference unit. This is an important finding, especially for policy makers, who may use scientific studies to inform their policies. I therefore want to shortly explore how this may affect the insights I presented in this thesis.

I will use two examples for this. First, the standard reference unit in today's academic literature on material stock in housing, which I also used, the MI per one $m^2$ (Arceo et al., 2023). Second, I want to capture the function of shelter provision of housing. Arceo et al. (2023) used material requirements per one bedroom as their functional unit to capture that function. Because this data is not available to me, I used the functional unit of mass per one household (Geodata AS, 2022). As the number of households differs between building types I used the average number of households per house type. No data on the potential household sizes was available.

No considerable differences between the concrete requirements of foundations between the different building types could be found using the first reference unit, one $m^2$ useful floor area (see Figure 5.3-1.) Using the second reference unit, one household, shows more pronounced differences between the building types (see Figure 6.6-1). In that case single-family houses use about three times more concrete in the foundation per household than assisted and communal living. Therefore, one could make very different policy recommendations when only using Figure 5.3-1. or Figure 6.6-1 to inform one's policy making.

A further exploration of the tradeoffs between different reference unit goes beyond the scope of this thesis. However, it is crucial to be aware of potential tradeoffs, especially when trying to form policy advice based on research. Discussing alternatives is essential, because it allows people to consciously select reference units while also being aware of their potential disadvantages. This is especially important for policymakers who determine the future developments of entire countries. All in all, this means that the insights from my thesis and my recommendations for the Trondheim municipality are still relevant. Policy makers should just be aware of the decisions, like the selection of the reference unit, and their consequences, that are part of this research.

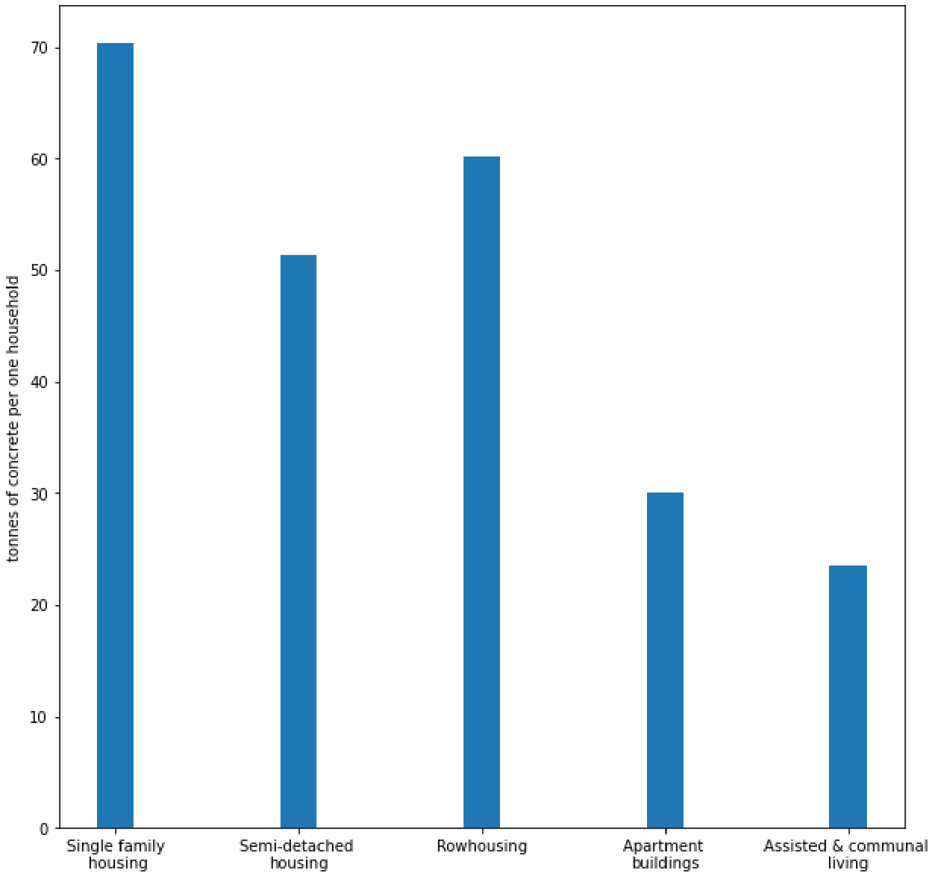


*Figure 6.6-1: Concrete use in the foundation per one household disaggregated by house types. The results were disaggregated by house types, because the different house types contain different numbers of households.*

## 6.7 Limitations

Models are a simplified representation of the real world. They simplify relationships and dependencies to estimate outcomes. This necessarily comes with limitations. The model limitations are grouped into 1) functional limitations and 2) data limitations.

To ensure the functionality of the model certain assumptions had to be made. The assumptions on weight distribution and foundation dimensions are crucial to examine as they influence model results. The model always assumes an equal distribution of the building weight across the whole building footprint. This assumption was necessary due to the lack of explicit load location data. As a result, the model assumes a foundation with homogenous bearing capacity across the whole building footprint. In reality loads may differ across the building footprint due to the construction of balconies, in-house garages or terraces that may be included in the building footprint. This would cause a different load distribution across the foundation and may therefore increase or decrease the required bearing capacity of the foundation.

A second assumption, that on the foundation dimensions, was necessary. Deep piles, for example, may be adapted in their dimensions to fit the specific construction site. Especially the length of the piles is adjusted so that they reach just onto the next load bearing soil layer. A 5-meter length may thus in some cases be an overestimation and in others an underestimation. It is even possible that the pile length differs within the same construction site because the bearing soil layer may be lower on one side of the building footprint than on the other. Especially the deep pile dimensions significantly affect the material use on peat and bog soils. If, therefore, deep piles are usually considerably shorter in Trondheim than expected, this would reduce the high material requirements of building on peat and bog soil.

Besides the necessary assumptions to run the model there are also four aspects which are not considered by the model that would complete the insights on foundations' material requirements. Firstly, the model does not estimate the use of steel in the foundation. While it is likely that concrete makes up the largest part of the foundation it is, nevertheless, mostly reinforced concrete that is used in foundations. Thus, to accurately estimate the material mass of foundations steel should be included in further developments of the model. Furthermore, two aspects of foundations are also left out of the model: 1) possible bearing structures inside basements and 2) parking garages as foundations. However, parking garages may require more concrete due to the higher loads from heavy cars. Thus, including parking garages as foundations may increase material requirements of certain buildings. The reason for exclusion is that it would have been very complicated to accurately determine which building includes a parking garage, because they are registered separately in the cadaster dataset. Moreover, a random sample has shown that parking garages sometimes spread under multiple large buildings to form shared garages. Thus, methods to attribute these cases to multiple buildings would have to be devised. Possible bearing structures in basements were also not considered, due to the increased complexity of their calculation. These are likely, however, to be only relevant to large buildings with basements where the span width of the basement is too large to be carry the above-ground structure on just the ceiling and the load bearing walls on the side.

There are some data limitations. Because no data on soil types across Trondheim at a relevant depth for building construction could be found I had to use a topsoil map. While this is a simplification of reality the impact of this choice is likely low, because all foundations, except the deep piles, do not reach lower into the ground than about 1 meter. Moreover, soil specific data such as bearing capacities and foundation dimensions were mostly sourced from grey literature. While information was cross-checked with other sources these were also grey literature. A verification of some data was done with professors from NTNU; however, they were not able to audit the entire model due to their time constraints (Dr. A. M. Selberg, personal communication, 1.12.2022; Dr. T. Kanstad, personal communication, 5.12.2022).

Lastly, the model results contain uncertainty. This uncertainty comes from the data quality of the sources used to build the model. These sources range from peer-reviewed academic publications to online blog websites. A major challenge was to find representative data for foundations and soil specific values. Only one source, Long et al. (2022), was, for example, available for soil specific data for Trondheim. All other sources had either no geographic origin specified or were not from Trondheim. In general, academic, and peer-reviewed sources were treated as reliable. Information from websites was treated as medium reliable when it contained references to academic or governmental publications and treated as having limited reliability when being unreviewed and unreferenced. For sources with limited reliability, I tried to corroborate their information by checking other websites with similar content. I then only used the information that was mentioned across multiple different websites. Lastly, in the case of spread footing foundations, I had to rely on my own guesses to estimate the archetypical dimensions, because there was no data available. Appendix D provides an in-depth overview of the various sources and their reliability. The evaluation process of the sources was inspired by Laner et al. (2016), but adapted for a purely qualitative evaluation of the sources.

As the model processes over 3500 buildings this causes some uncertainties in the individual results of each house, because of uncertain input data, for example for the soil type. Therefore, it is likely that some results may be under- or overestimated. However, through aggregation these estimations can balance each other out. A potential skewedness of the model results would propagate through to the aggregated results. Therefore, a certain variability in the results was considered when interpreting the results. This led, for example, to the conclusion that housing types are not very significant, as their different MIs could simply be due to model variability. As of yet, the model uncertainties have not been tested. However, they should be tested, before any further research is conducted using this model.

# 7 Conclusion

This thesis researched how the house type and soil type affect the material requirements of residential buildings built between 2010 and 2020 in Trondheim. This is useful as most housing stock analysis in the literature focus on building structures above the ground. This thesis thus helps to determine whether foundations should be considered a relevant part of the material stock in a house or not. Due to the inability of obtaining data from the industry I developed a Python-based model to estimate the concrete requirements of foundations. All in all, seven insights come from this thesis project.

First, 507 000 tonnes of concrete from residential building foundation construction between 2010 and 2020 were added to the material stock. This produced about 50 000 tonnes of $CO_2$ eq. emissions from production plus about 506 tonnes of $CO_2$ eq. emissions from last-leg transportation. Therefore, transport emissions are minuscule (1%) compared to the concrete production emissions. This is due to the greatly higher emission factor of concrete production. Nevertheless, there are two strategies to reduce transport emissions: 1) by reducing the material need of the foundation, because that will reduce the need for transportation and 2) by using alternative fuels or engine technologies of the trucks.

Second, the MI factors for foundations of all five analyzed building types are similar. Thus, no building can be said to be considerably more or less materially efficient in terms of material requirements of their foundation than another. The reasons for that are likely that while small buildings have lighter foundations, they also have less UFA. Large buildings, on the other hand, have very heavy foundations, but also more UFA, thus equalizing the extra material needed. A similar pattern can be observed when comparing buildings with a basement to buildings without one. While a basement increases material requirements it also adds UFA. This dampens the increase of the building's MI factor. As a result, the MI differences between a building with and a building without a basement are minor.

Third, the most considerable insight of this thesis is that building on peat and bog soils increase material requirements of the foundation by 80% compared to all other soils in Trondheim. This is due to the need for deep pile foundations, which require a lot of material. Less materially intense shallow foundations can be constructed on all other soils.

Fourth, the mass distribution in buildings based on the model aligns with the distribution found in other papers (Arceo et al., 2023; Gontia et al., 2018). This supports the findings of this thesis. According to the model foundations, make up 70% of the entire building's material mass in smaller buildings and 30% in larger buildings. From that I concluded that especially when thinking about reusing material from smaller buildings, the foundation should be considered. For larger buildings the focus should lie on the above-ground structure, where light materials like wood could provide stability, while at the same time reducing building weight and thus the material requirements of the foundation. All in all, I argue that foundations should become part of the stock considerations when planning circular economies, because 1) only then potential reuse options for the foundations will be considered and 2) this will help balance material in- and outflows in urban metabolism research (Tanikawa & Hashimoto, 2009).

Fifth, the current residential zoning plans of Trondheim until 2034 only overlap 5% with peat and bog areas. However, because the foundation's material needs are 80% higher on peat and bog and these plans are still open to changes, I recommend that the municipality considers adapting its plans. I furthermore suggest that peat and bog zones should be either avoided or adapted into the zoning plans. Building zones that are soil specific should be developed to regulate that only light structures that do not need foundations are built or natural recreation areas are planned on peat and bog. By creating these zones, peat and bog areas become immediately recognizable in city planning and can be organically integrated into the new expansion plans.

Sixth, the discussion of the reference unit shows that with a changing of the reference unit potential conclusions and policy advise may change. It is thus crucial that policy makers and academics are aware of potential tradeoffs and take these into account when making decisions.

Lastly, and most importantly, I argue that the soil type that buildings are built upon should be considered when developing archetypical buildings. In past literature buildings have been distinguished, for example, by their age, by their loadbearing structure and by their type (single-family vs. multi-family, etc.). They were disaggregated because research identified considerable material differences along these distinguishing factors. My research has show that considerable material differences can also be found when distinguishing between the soil types that housing is standing on. I therefore argue that soil types should be taken into consideration as a distinguishing feature in future research.

# 8 Bibliography

Abebe, A., & Smith, I. G. (2022). *Pile Foundation Design: A Student Guide*.

AF Math & Engineering (Director). (2018, October 18). *How to Design a Strip Footing—Structural Design Part 1/2*. https://www.youtube.com/watch?v=TCjNMcX92NI

Ajayebi, A., Hopkinson, P., Zhou, K., Lam, D., Chen, H.-M., & Wang, Y. (2021). Estimation of structural steel and concrete stocks and flows at urban scale–towards a prospective circular economy. *Resources, Conservation and Recycling*, *174*, 105821. https://doi.org/10.1016/j.resconrec.2021.105821

Aqua-calc. (2022). *Density of Sand with Gravel, dry (material)*. https://www.aqua-calc.com/page/density-table/substance/sand-blank-with-blank-gravel-coma-and-blank-dry

Arceo, A., MacLean, H. L., & Saxe, S. (2023). Material intensity in single-family dwellings: Variability between locations, functional unit and drivers of material use in Toronto, Perth, and Luzon. *Resources, Conservation and Recycling*, *188*, 106683. https://doi.org/10.1016/j.resconrec.2022.106683

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

Betong Øst. (2020). *Før du bestiller*. https://betongost.no/leveringsmetoder/for-du-bestiller/

Betong Øst. (2022). *Prisliste betong pr 01.07.2022*. https://betongost.no/wp-content/uploads/2022/06/2022-07-Betong-Trondelag.pdf

Betongsentrum.no. (2022). *Betongbiler og utstyr*. Betongsentrum.no. https://www.betongsentrum.no/betongbiler-og-utstyr/

Boeing, G. (2017). OSMnx: New methods for acquiring, constructing, analyzing, and visualizing complex street networks. *Computers, Environment and Urban Systems*, *65*, 126–139. https://doi.org/10.1016/j.compenvurbsys.2017.05.004

Cao, X., Yue, M., Xu, H., Chen, S., Hou, Y., & Wang, X. (2021). The Technology and Application of Improving Bearing Capacity of Deep Peat Soil Subgrade. *E3S Web of Conferences*, *272*, 01010. https://doi.org/10.1051/e3sconf/202127201010

Condeixa, K., Haddad, A., & Boer, D. (2017). Material flow analysis of the residential building stock at the city of Rio de Janeiro. *Journal of Cleaner Production*, 19.

Davis, S. J., Lewis, N. S., Shaner, M., Aggarwal, S., Arent, D., Azevedo, I. L., Benson, S. M., Bradley, T., Brouwer, J., Chiang, Y.-M., Clack, C. T. M., Cohen, A., Doig, S., Edmonds, J., Fennell, P., Field, C. B., Hannegan, B., Hodge, B.-M., Hoffert, M. I., … Caldeira, K. (2018). Net-zero emissions energy systems. *Science*, *360*(6396), eaas9793. https://doi.org/10.1126/science.aas9793

Dream Civil. (2022). *Density of Sand in Kg/m3: Density of Dry Sand, Loose Sand, Packed Sand & M sand*. https://dreamcivil.com/density-of-sand/

Ellis, L. D., Badel, A. F., Chiang, M. L., Park, R. J.-Y., & Chiang, Y.-M. (2019). Toward electrochemical synthesis of cement: An electrolyzer-based process for decarbonating CaCO3 while producing useful gas streams. *Proceedings of the National Academy of Sciences*, *117*(23), 12584–12591. https://doi.org/10.1073/pnas.1821673116

Engineers Edge. (2022). *Soil Cohesion Table*. https://www.engineersedge.com/civil_engineering/soil_cohesion_table_13905.htm

Esri, Artz, M., & Baumann, J. (2009). What Is The Geographic Approach? *ArcNews Online*. https://www.esri.com/news/arcnews/fall09articles/what-is-geographic.html

FABEKO. (2022). *Medlemsoversikt*. FABEKO. https://fabeko.no/medlemmer-i-fabeko/medlemsoversikt/

Geodata AS. (2022). *Eiendom / matrikkel—GeomapMatrikkel*. Eiendom | Geodata Online. https://dokumentasjon.geodataonline.no/docs/Temakart/Eiendom/

Geodata AS. (2023). *Administrative grenser | Geodata Online*. https://dokumentasjon.geodataonline.no/docs/Temakart/Administrative grenser/

Geotechdata.info. (2013). *Angle of friction*. https://www.geotechdata.info/parameter/angle-of-friction

Geotechdata.info. (2015). *Soil bearing capacity*. http://www.geotechdata.info/parameter/bearing-capacity

Gontia, P., Nägeli, C., Rosado, L., Kalmykova, Y., & Österbring, M. (2018). Material-intensity database of residential buildings: A case-study of Sweden in the international context. *Resources, Conservation and Recycling*, *130*, 228–239. https://doi.org/10.1016/j.resconrec.2017.11.022

Gontia, P., Thuvander, L., Ebrahimi, B., Vinas, V., Rosado, L., & Wallbaum, H. (2019). Spatial analysis of urban material stock with clustering algorithms: A Northern European case study. *Journal of Industrial Ecology*, *23*(6), 1328–1343. https://doi.org/10.1111/jiec.12939

Göswein, V., Gonçalves, A. B., Silvestre, J. D., Freire, F., Habert, G., & Kurda, R. (2018). Transportation matters – Does it? GIS-based comparative environmental assessment of concrete mixes with cement, fly ash, natural and recycled aggregates. *Resources, Conservation and Recycling*, *137*, 1–10. https://doi.org/10.1016/j.resconrec.2018.05.021

Gursel, P. A., Masanet, E., Horvath, A., & Stadel, A. (2014). Life-cycle inventory analysis of concrete production: A critical review. *Cement and Concrete Composites*, *51*, 38–48. https://doi.org/10.1016/j.cemconcomp.2014.03.005

Heeren, N., & Fishman, T. (2019). A database seed for a community-driven material intensity research platform. *Scientific Data*, *6*(1), 23. https://doi.org/10.1038/s41597-019-0021-x

Heidelberg Cement Group. (2022). *Norway*. HeidelbergCement Group. https://www.heidelbergcement.com/en/norway

HGC India. (2018, August 16). Foundation Types depends on Soil Types and Other Factors. *HGC India*. https://hgcindia.in/foundation-types-depends-on-soil-types-and-other-factors/

Hu, M. (2010). *Dynamic material flow analysis to support sustainable built environment development* [Doctor Thesis, Universteit Leiden]. https://scholarlypublications.universiteitleiden.nl/access/item%3A2877690/view

Jang, H.-S., Zhang, Q.-Z., Kang, S.-S., & Jang, B.-A. (2018). Determination of the Basic Friction Angle of Rock Surfaces by Tilt Tests. *Rock Mechanics and Rock Engineering*, *51*(4), 989–1004. https://doi.org/10.1007/s00603-017-1388-7

Jones, F. (2018). *Geophysics foundations: Physical properties: Density*. https://www.eoas.ubc.ca/courses/eosc350/content/foundations/properties/density.htm

Kartverket. (2023). *Føringsinstruks for matrikkelen: Kartverket eiendomsdivisjonen Matrikkel- og stedsnavnavdelingen*. https://www.kartverket.no/globalassets/eiendom/matrikkel/foeringsinstruks-matrikkelen.pdf

Kleemann, F., Lederer, J., Rechberger, H., & Fellner, J. (2016). GIS-based Analysis of Vienna’s Material Stock in Buildings: GIS-based Analysis of Material Stock in Buildings. *Journal of Industrial Ecology*, *21*(2), 368–380. https://doi.org/10.1111/jiec.12446

Komurlu, E., & Durmus Demir, A. (2018). Determination of Cohesion values of Rock Materials using Double Shear Jaws. *Periodica Polytechnica Civil Engineering*. https://doi.org/10.3311/PPci.12043

Krausmann, F., Wiedenhofer, D., Lauk, C., Haas, W., Tanikawa, H., Fishman, T., Miatto, A., Schandl, H., & Haberl, H. (2017). Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use. *Proceedings of the National Academy of Sciences*, *114*(8), 1880–1885. https://doi.org/10.1073/pnas.1613773114

Lanau, M., Liu, G., Kral, U., Wiedenhofer, D., Keijzer, E., Yu, C., & Ehlert, C. (2019). Taking Stock of Built Environment Stock Studies: Progress and Prospects. *Environmental Science & Technology*, *53*(15), 8499–8515. https://doi.org/10.1021/acs.est.8b06652

Laner, D., Feketitsch, J., Rechberger, H., & Fellner, J. (2016). A Novel Approach to Characterize Data Uncertainty in Material Flow Analysis and its Application to Plastics Flows in Austria. *Journal of Industrial Ecology*, *20*(5), 1050–1063. https://doi.org/10.1111/jiec.12326

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

Lehne, J., & Preston, F. (2018, June). *Making Concrete Change: Innovation in Low-carbon Cement and Concrete* [Chatham House Report]. Chatham House Report. https://www.chathamhouse.org/sites/default/files/publications/research/2018-06-13-making-concrete-change-cement-lehne-preston.pdf#CHHJ6042-Cement-report-180611.indd%3A.18769%3A4601

Long, M., Paniagua, P., Grimstad, G., Trafford, A., Degago, S., & L'Heureux, J.-S. (2022). Engineering properties of Norwegian peat for calculation of settlements. *Engineering Geology*, *308*, 106799. https://doi.org/10.1016/j.enggeo.2022.106799

Lotfi, S., Eggimann, M., Wagner, E., Mróz, R., & Deja, J. (2015). Performance of recycled aggregate concrete based on a new concrete recycling technology. *Construction and Building Materials*, *95*, 243–256. https://doi.org/10.1016/j.conbuildmat.2015.07.021

Marinova, S., Deetman, S., van der Voet, E., & Daioglou, V. (2020). Global construction materials database and stock analysis of residential buildings between 1970-2050. *Journal of Cleaner Production*, *247*, 119146. https://doi.org/10.1016/j.jclepro.2019.119146

Mastrucci, A., Marvuglia, A., Popovici, E., Leopold, U., & Benetto, E. (2017). Geospatial characterization of building material stocks for the life cycle assessment of end-of-life scenarios at the urban scale. *Resources, Conservation and Recycling*, *123*, 13. http://dx.doi.org/10.1016/j.resconrec.2016.07.003

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

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

Munro, R. (2005). Dealing with poor bearing capacity on low volume roads on peat in the Northern Periphery. *Proceedings of the International Conferences on the Bearing Capacity of Roads, Railways and Airfields*. https://www.ntnu.no/ojs/index.php/BCRRA/article/view/3176

NGU. (2022). *Datasett og nedlasting [Datasett "Løsmasser"]*. https://www.ngu.no/emne/datasett-og-nedlasting

Norcem. (2022). *Cement production and emissions*. https://www.norcem.no/en/Cement_and_CCS

Norwegian Ministry of Climate and Environment. (2019). *Norway's National Plan related to the Decision of the EEA Joint Committee No. 269/2019 of 25 October 2019*. Norwegian Ministry of Climate and Environment. https://www.regjeringen.no/contentassets/4e0b25a4c30140cfb14a40f54e7622c8/national-plan-2030_version19_desember.pdf

NTNU. (2023). *Circular City*. https://www.ntnu.edu/sustainability/circularcity

Oksholen, T. (2006, December 4). *Torvmose—Ei tikkande klimabombe [in Norwegian]*. https://forskning.no/vaer-og-vind-klima-miljovern/torvmose---ei-tikkande-klimabombe/1027010

Ostrolensk, B. (1941). *Economic Geography* (5th ed.). Irwin Publishers.

Pauliuk, S., Wang, T., & Müller, D. B. (2013). Steel all over the world: Estimating in-use stocks of iron for 200 countries. *Resources, Conservation and Recycling*, *71*, 22–30. https://doi.org/10.1016/j.resconrec.2012.11.008

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

Portland Cement Association. (2022). *How Cement Is Made*. How Cement Is Made. https://www.cement.org/cement-concrete/how-cement-is-made

Rajapakse, R. A. (2008). *Geotechnical Engineering Calculations and Rules of Thumb* (1st ed.). Butterworth-Heinemann. https://web-p-ebscohost-com.ezproxy.leidenuniv.nl/ehost/ebookviewer/ebook/ZTAwMHh3d19fMjQ5Mjk0X1

9BTg2?sid=688562d4-e5a4-4037-968d-e2f0190ef0d6%40redis&vid=0&format=EB&rid=1

Sharma, P. V. (1997). *Environmental and Engineering Geophysics*. Cambridge University Press. http://dx.doi.org/10.1017/CBO9781139171168.002

Sprecher, B., Verhagen, T. J., Sauer, M. L., Baars, M., Heintz, J., & Fishman, T. (2022). Material intensity database for the Dutch building stock: Towards Big Data in material stock analysis. *Journal of Industrial Ecology*, *26*(1), 272–280. https://doi.org/10.1111/jiec.13143

Standard Norge. (2010). *Eurokode 2: Prosjektering av betongkonstruksjoner Del 1-2: Brannteknisk dimensjonering* (NS-EN 1992-1-2:2004+NA:2010; Eurocode). Norsk Standard.

Standard Norge. (2023). *Eurokode 7*. Eurocode 7. https://www.standard.no/no/nettbutikk/produktkatalogen/produktpresentasjon/?ProductID=424316

Statistisk sentralbyrå. (2000). *Classification of type of building /cadastre*. https://www.ssb.no/klass/klassifikasjoner/31

Statistisk sentralbyrå. (2022). *Kommunefakta Trondheim (Trøndelag—Trööndelage)*. SSB. https://www.ssb.no/kommunefakta/kommune

Struct X. (2022). *Densities of Different Soil Types*. https://structx.com/Soil_Properties_002.html

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

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

The Constructor. (2020, November 10). *Thumb Rules and Specifications for Design of Reinforced Concrete Beam*. The Constructor. https://theconstructor.org/practical-guide/assumptions-specifications-design-reinforced-concrete-beam/233721/

Tomiša, A. (2019, July 25). *Types of shallow foundations and their characteristics I Geotech d.o.o. I*. Geotech. https://www.geotech.hr/en/types-of-shallow-foundations/

Trondheim Municipality. (2021). *Klimaplan og klimaarbeid*. Trondheim kommune. https://www.trondheim.kommune.no/klimaplan/

Trondheim Municipality. (2022, April 11). *Kommuneplanens arealdel 2022-2034: Bestemmelser og retningslinjer*. https://drive.google.com/file/d/19k-5PNJT14bfvMh_I6yb7pKQdPnutxQU/view

Turskis, Z., Daniūnas, A., Zavadskas, E. K., & Medzvieckas, J. (2016). Multicriteria Evaluation of Building Foundation Alternatives: Multicriteria evaluation of building foundation alternatives. *Computer-Aided Civil and Infrastructure Engineering*, *31*(9), 717–729. https://doi.org/10.1111/mice.12202

UNFCCC. (2022). *The Paris Agreement*. https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

Unicon. (2022). *PRISLISTE OKTOBER 2022* [Business website]. PRISLISTER. https://www.unicon.no/media/qxfp3ea0/prisliste-tr%C3%B8ndelag-2022.pdf

Valsasina, L., & Ecoinvent Centre. (2022). *Market for transport, freight, lorry 16-32 metric ton, EURO6, RER, allocation, cut-off by classification, ecoinvent database version 3.9*.

Van den Berghe, K. B. J., & Verhagen, T. J. (2021). Making it Concrete: Analysing the Role of Concrete Plants' Locations for Circular City Policy Goals. *Frontiers in Built Environment*, *7*. https://www.frontiersin.org/articles/10.3389/fbuil.2021.748842

Vásquez, F., Løvik, A. N., Sandberg, N. H., & Müller, D. B. (2016). Dynamic type-cohort-time approach for the analysis of energy reductions strategies in the building stock. *Energy and Buildings*, *111*, 37–55. https://doi.org/10.1016/j.enbuild.2015.11.018

Werner, F., & Ecoinvent Centre. (2022). *Concrete production, 25MPa, for building construction, with cement, CEM II/A - CH - concrete, 25MPa, allocation, cut-off by classification, ecoinvent database 3.9*.

Worldbank. (2023). *Norway Cement; portland, other than white, whether or not artificially coloured imports by country | 2019 | Data*. https://wits.worldbank.org/trade/comtrade/en/country/NOR/year/2019/tradeflow/Imports/partner/ALL/product/252329

Zhang, C., Hu, M., Dong, L., Xiang, P., Zhang, Q., Wu, J., Li, B., & Shi, S. (2018). Co-benefits of urban concrete recycling on the mitigation of greenhouse gas emissions and land use change: A case in Chongqing metropolis, China. *Journal of Cleaner Production*, *201*, 481–498. https://doi.org/10.1016/j.jclepro.2018.07.238

Zhang, L., Yang, J., Cai, Z., & Yuan, Z. (2015). Understanding the Spatial and Temporal Patterns of Copper In-Use Stocks in China. *Environmental Science & Technology*, *49*(11), 6430–6437. https://doi.org/10.1021/acs.est.5b00917

# 9 Supporting Information Explanation

The supporting information consists of 14 files. The table below gives an overview of the files, their content and their purpose.

*Table 9-1: Overview of the supporting information of this thesis.*

| File name | Category | Content | Purpose | Source |
|---|---|---|---|---|
| buildings_with_neighborhoods.csv | Foundation model input | Neighborhood of each house | I created this dataset by overlaying the cadaster and the neighborhood data. Used to assign the corresponding neighborhood each house is in. | Inputs:<br>Geodata AS (2023)<br>Matrikkel: Geodata AS (2022)<br>Dataset: my own work |
| distance_model_v3.ipynb | Transport model | Python code | Estimates the shortest travel distances between the concrete suppliers and the construction sites | Boeing (2017)<br>My own work |
| distance_results.xlsx | Outcomes dataset | Travel distances between concrete suppliers and houses | This was used to store the transport distance from the concrete suppliers to each house. By multiplying the results with an emission factor I got the transport emissions. | Transport model |
| dynamic foundation model.xlsx | Foundation model input | Constants | Contains constants used for the Therzagi bearing capacity calculation in the foundation model. | Rajapakse (2008) |
| foundation_model.py | Foundation model | Python code | Contains the code to apply the foundation formulas to each house. | My own work, based on formulas by Rajapakse (2008) |
| housing_coordinates.xlsx | Transport model input | House coordinates | Contains the coordinates of the center point of each house in the dataset. Used as the end point for the transport model. | Inputs: Geodata AS (2022)<br>Dataset: my own work |

| File name | Category | Content | Purpose | Source |
|---|---|---|---|---|
| housing_data_complete.xlsx | Foundation model input | Cadaster data | Contains all the housing data from the cadaster (Matrikkel) used for the foundation calculation. | Geodata AS (2022) |
| living_units_per_house.csv | Foundation model input | Number of households per building in the cadaster | Used for later analysis, specifically to explore alternative reference units than m$^2$ useful floor area. | Geodata AS (2022) |
| results_slab_always_undereta_yes_base_ceil_only_tall.xlsx | Foundation model output | Model results | The resulting dataset output of the foundation model. The complicated name specifies the settings chosen in the model. For more information on the naming convention see the foundation model Python code. | Foundation model |
| soiltypes.xlsx | Foundation model input | Constants + foundation lookup table for the foundation model | It supplies the model with the soil specific data to make the bearing capacity calculations. It is also the file where it is specified which foundation is used on which soil and house. | Various sources. Check file for more insights. |
| terzaghi_bearing_capacity_formulas.py | Foundation model input | The bearing capacity formulas | Separate file containing geotechnical engineering formulas as Python functions. | Based on Rajapakse (2008)<br>Put into code by me |
| Trondheim.graphml | Transport model input | Trondheim's street network | This dataset contains Trondheim's street network and is used by the transport model to figure out the shortest path between two coordinates using the roads in Trondheim. | Automatic download from Open Street Maps by OSMnx library created by Boeing (2017) |

# 10 Appendix A

Constants of the Terzaghi bearing capacity formulas from Rajapakse (2008).

*Table 10-1: Terzaghi bearing capacity factors.*

| Friction angle (ϕ) [in °] | Nc | Nq | Ny |
|---|---|---|---|
| 0 | 5.7 | 1 | 0 |
| 5 | 7.3 | 1.6 | 0.5 |
| 10 | 9.6 | 2.7 | 1.2 |
| 15 | 12.9 | 4.4 | 2.5 |
| 20 | 17.7 | 7.4 | 5 |
| 25 | 25.1 | 12.7 | 9.7 |
| 30 | 37.2 | 22.5 | 19.7 |
| 35 | 57.8 | 41.4 | 42.4 |
| 40 | 95.7 | 81.3 | 100.4 |
| 45 | 172.3 | 173.3 | 297.5 |
| 50 | 347.5 | 415.1 | 415.1 |

*Table 10-2: Terzaghi shape factors.*

| Footing type | Sc | Sy |
|---|---|---|
| square footing | 1.3 | 0.8 |
| strip footing | 1 | 1 |
| round footing | 1.3 | 0.6 |

# 11 Appendix B

Assumed foundation dimensions.

*Table 11-1: Foundation dimensions assumed by the foundation model.*

| Foundation type | Foundation part | Dimensions (m) | Source/Logic |
|---|---|---|---|
| Deep pile | Pile diameter | 0.5 | Diameter of piles in the Realfagbygget (NTNU) buidling load bearing structure |
| | Pile length | 5 | Long et al. (2022) |
| Slab | Width ∗ length | Building footprint | Has to cover entire building footpring |
| | Slab height (small buildings) | 0.1 | (Dr. A. M. Selberg, personal communication, 1.12.2022; Dr. T. Kanstad, personal communication, 5.12.2022) |
| | Slab height (large buildings) | 0.2 | |
| Strip | Footing starting breadth | 0.5 | Bearing capacity at 0.5 m calculated. If too low, then continuously increased by 10 cm until sufficient |
| | Footing height | 0.2 | AF Math & Engineering (2018) |
| | Footing length | Always 1 meter, then scaled up | Footing designed to hold lineload of 1m. So concrete volume for 1m calculated. Then volume multiplied with circumference of building footprint as the foundation runs along the outer walls of the house. |
| | Wall height (above T bar) | 0.2 | Small values, as shallow foundations should be as small as possible. In Trondheim they often reach just below the surface as frost insulation is used (Dr. T. Kanstad, personal communication, 28.02.2023) No outside verification was achieved. |
| | Wall width (above T bar) | 0.2 | |
| Spread footing | Footing side length | 0.4 | |
| | Footing height | 0.2 | |
| | Pile height | 0.2 | |
| | Pile width | 0.2 | |
| | Pile depth | 0.2 | |
| Basement | Wall height | 2.5 | Ceiling height in own house, though house was built before 2010. |
| | Wall thickness | 0.2 | Based on fireproof wall standards in Norwegian building code (Standard Norge, 2010) |

# 12 Appendix C

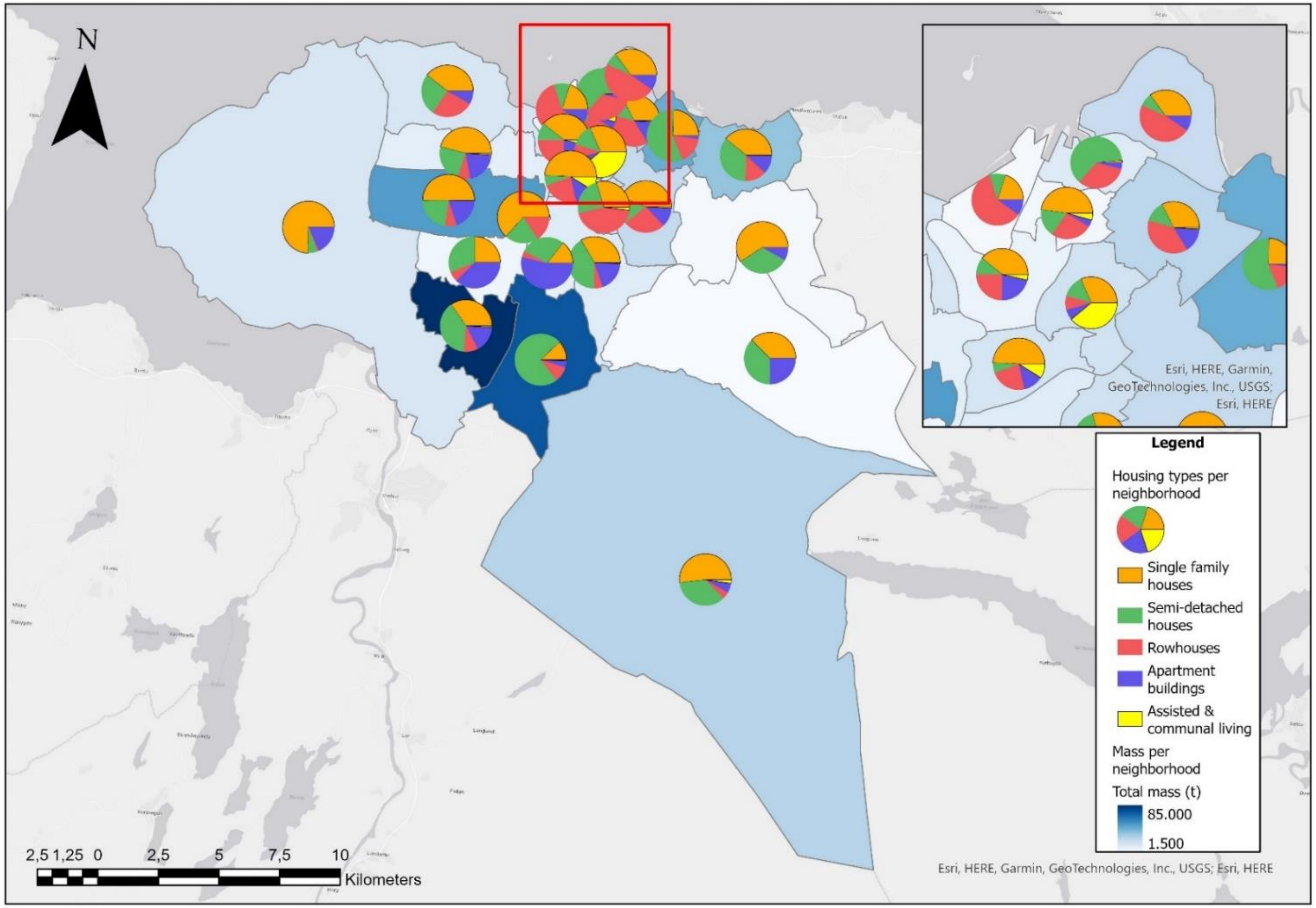


*Figure 6.7-1: Map showing the concrete stock additions through foundation construction per neighborhood in blue (the darker the more). The pie charts show the share of building types newly construction in each neighborhood between 2010 and 2020. Map based on the foundation model results and Geodata AS (2022).*

# 13 Appendix D

An overview across three tables of all the sources used in the model. To see what sources influenced the foundations see Appendix B. To see which sources supplied which data on the soil types see the Supporting Information.

*Table 13-1: An evaluation of the sources used as input for the information on houses in Trondheim.*

| Source | Used for | Reliability | Applicability |
|---|---|---|---|
| Geodata AS (2022) | Building type<br>Number of basement floors<br>Building footprint<br>Building weight<br>Building location | Data sourced from governmental agencies. Can be considered reliable. | The data, the cadaster dataset, was specifically made for the purpose I used it for. |
| NGU (2022) | Soil type | Academic institute using field test-generated data. Can be considered reliable. | The data was developed for spatial analysis of soil distribution and urban planning (NGU, 2022). While not ideal for foundation planning, as it only covers to the topsoil layers, it was the best data available. |
| Gontia et al. (2018) | Building weight (MI factor for Norwegian houses) | Peer-revied article. Can be considered reliable. | The MI factor was developed for Sweden. Overlap in construction techniques between Sweden and Norway gives this good applicability. |

*Table 13-2: An evaluation of the sources used as input for the information on foundations in Trondheim.*

| **Source** | **Used for** | **Reliability** | **Applicability** |
|---|---|---|---|
| T. Kanstadt, personal communication, 5.12.2022 | Slab foundation<br>Strip foundation | Professor at NTNU, Department of Structural Engineering. Can be considered reliable. | I asked the professor specifically about these foundation types, so that his answers were very applicable. |
| Long et al. (2022) | Deep pile foundation | Peer-reviewed article. Can be considered reliable. | The paper assessed peat and bog soil layer depths in the Trondheim municipality. Thus, great applicability. |
| Rajapakse (2008) | Terzaghi bearing capacity formula<br>Foundation archetypes | Academic book on established engineering practices. Can be considered reliable. | Rajapakse wrote the book with a background of construction in Canada. The formulas can of course also be used in Europe. Where necessary I replaced constant values in functions stemming from Canadian building code with those in Norwegian building code. |
| Dr. A. M. Selberg, personal communication, 1.12.2022 | Slab foundation | Professor at NTNU, Department of Structural Engineering. Can be considered reliable. | I asked the professor specifically about these foundation types, so that his answers were very applicable. |
| AF Math & Engineering (2018) | Strip foundation | YouTube tutorial video on strip foundation calculations. Values presented | The video talks about calculating the dimensions of a foundation for a specific load. Only the foundation height value was used from this video. While it is not directly ensured that this value is realistic, it was the best data I could find. |
| Standard Norge (2010) | Basement walls | This is the official Norwegian building code, which specifies building requirements in Norway. It can thus be regarded as reliable. | While the walls discussed in the code were not basement walls, it discussed walls being only exposed on one side. This was taken as close enough, as no other data source was available. |
| The author | Spread footing foundation<br>Basement | The reliability can be considered low. I am no expert in foundation construction and the values from me are best guesses. | I only resorted to guessing values myself when there were no other sources to be found. I tried my best to base my guesses on something measurable, such as my own basement, where possible. |

| Source | Used for | Reliability | Applicability |
|---|---|---|---|
| Abebe & Smith (2022) | Foundation archetypes | A student guide of pile foundation design by professors at the Napier University, Edinburgh. While not a peer-reviewed publication, it is written by academics from the field as an educational resource, thus giving it good reliability. | It only introduces pile foundations; thus it does not provide an overview over typical foundation types. However, the source was used in combination with other sources to find which foundation types were most talked about. Thus it was applicable to the topic at hand, |
| HGC India (2018) | Foundation archetypes | A website from an Indian construction company. As industry professionals they are likely to have good knowledge of foundation types. Due to it being an unreviewed source, its reliability is considered medium to low. | The website introduces various types of foundations. While not going into lots of detail it served as a good overview of common foundation types, thus having a high applicability. |
| The Constructor (2020) | Foundation archetypes | The constructor is an online website with articles for civil engineers. As a non-peer-reviewed source on the internet its reliability is limited. | The website talks about beam design, which was necessary to develop the archetypical foundations. As very little other information on beam design was available at the level needed, this source was chosen. |
| Tomiša (2019) | Foundation archetypes | Croatian company website for geotechnical investigations. While being industry professionals their information is not peer-reviewed, thus limited reliability. | The website gives an overview of typical foundation types, thus being highly applicable for the goal of finding archetypical foundation types. |
| Turskis et al. (2016) | Foundation archetypes | This peer-reviewed academic publication assesses multicriteria evaluation of foundation alternatives. As a result, it can be considered reliable. | This source was used to get an overview of the existing foundation types. Used in conjunction with the grey literature sources which confirmed each other, this was used to determine the archetypical foundation types. |

*Table 13-3: An evaluation of the sources used as input for the information on soil types in Trondheim.*

| Source | Used for | Reliability | Applicability |
|---|---|---|---|
| Geotech.info (2013) | Soil friction angle (ϕ) | An unreviewed website that references various governmental or academic publications. This gives it a good reliability. | This source was highly applicable as it supplied the necessary data directly and with references to academic and governmental sources. |
| Jang et al. (2018) | Soil friction angle (ϕ) | A peer-reviewed academic publication in a journal. Thus, reliability can be considered high. | This source was applicable as it supplied friction angle data on bedrock. |
| Struct X (2022) | Soil density | Unreviewed website with unclear references to governmental and academic publications as additional resources. The reliability can be considered medium, as the website was developed with structural engineers in mind as the audience. | The data is not georeferenced, meaning the location of the sampling is unknown. However, USGS soil types were used to match densities in this table with the soils found in Trondheim. |
| Jones (2018) | Soil density | An unreviewed website from a professor at the UBC Earth and ocean Sciences Department. As a result, the data can be considered medium reliable. | The source lists densities for various rock types. I used an average of all rock densities. The data was not specific for Trondheim, but I am assuming similar densities in Trondheim. |
| Sharma (1997) | Soil density | The source is a published academic book, it can thus be considered reliable. | The book is about geophysics and discusses soil densities, but not for Trondheim specifically. |
| Dream Civil (2022) | Soil density | An unreviewed website displaying information from civil engineers for civil engineers. The data can be considered medium reliable. | It contains data on sand density, which I was specifically looking for here. |
| Aqua-calc (2022) | Soil density | An unreviewed website that publishes values on soil densities. | It was used to estimate the sand density in Trondheim, but its original location is unknown. |
| Engineers Edge (2022) | Soil cohesion | An unreviewed website containing a dataset with references to governmental publications. As such, it can be considered medium reliable. | The dataset contains typical soil cohesion values for soil types sorted by USGS typology. Thus, fits well for how I used it in my thesis. |
| Komurlu & Durmus Demir (2018) | Soil cohesion | An academic publication on soil cohesion with data from an experimental study. It can thus be considered reliable. | The data from the experiments was directly used as the soil cohesion values for my model. I assumed values are similar in Trondheim. |

| Source | Used for | Reliability | Applicability |
|---|---|---|---|
| Geotech.info (2015) | Soil bearing capacity | An unreviewed website that publishes values on soil bearing capacities with references to academic publications and building codes. Thus, it can be considered medium reliable. | The bearing capacity values were organized by USGS soil typology, so I could transfer them directly to my own soil types. As such, this source was very applicable. |