Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
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Steel in-use in Trondheim's residential building stock: quantification, embodied GHG emissions and mitigation options

Master's thesis in Industrial Ecology
Supervisor: Daniel B. Müller
Co-supervisor: Nils Dittrich

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Trondheim, 11.06.23

Abstract

The development of the built environment contributes significantly to global emissions, and the projected growth of the global building stock poses challenges to climate change mitigation. To address these issues, the circular economy will be fundamental. However, its implementation in the building sector remains limited, and there is a need for innovative approaches, such as urban mining, to exploit the material stock. Understanding the spatial and temporal aspects of building stocks, including material quantities and waste flows, enables stakeholders and policymakers to facilitate more reuse and reduce demand for virgin materials. Steel is one of the primary materials in the building stock and represents one of the biggest contributors to global GHG emissions. As such, this thesis is based on a bottom-up Material Flow Analysis model which quantifies and analyses the steel in the residential building stock in Trondheim. Using machine learning to estimate structural types, combined with specific MI coefficients, the steel stock of the cohorts 1990-2022 is characterised by structural type, use type and components. It was found that most of the steel exists in the foundations of all buildings and in the structural elements of steel buildings. In total, it was found that there are around 178 kilotons of steel in the stock, which has led to 173 kilotons of embodied CO_2-emissions. Some approaches for reducing final demand and increasing reuse and recycling are also discussed.

Sammendrag

Utviklingen av det bygde miljø bidrar betydelig til globale utslipp, og den forventede veksten i den globale bygningsmassen utfordrer arbeid mot utslippsreduksjon. For å takle disse utfordringene vil den sirkulære økonomien være viktig. Imidlertid er implementeringen i byggesektoren begrenset, og det er behov for innovative tilnærminger, som for eksempel urban gruvedrift, for å utnytte materialer i bygningsmassen. Å bedre forstå bygningsmassen, inkludert materialekvantiteter og avfallstrømmer, gjør det mulig for beslutningstakere å legge til rette for mer gjenbruk og redusere etterspørsel better jomfruelige ressurser. Stål er en av de primære materialene i bygningsmassen og representerer en av de største bidragsyterne til globale klimagassutslipp. Denne masteroppgaven basert på en bottom-up materialstrømanalyse-modell som kvantifiserer og analyserer stålet i bygningsmassen i Trondheim. Ved å bruke maskinlæring for å estimere strukturtyper, kombinert med spesifikke materialintensitet-faktorer, karakteriseres stålmengden fra kohortene 1990-2022 etter strukturtype, brukstype og bygningskomponenter. Det ble funnet at mesteparten av stålet finnes i fundamentet for alle type bygninger og i de strukturelle elementene til stålkonstruksjoner. Totalt sett ble det funnet at det er rundt 178 kilotonn stål i bygningsmassen, som har ledet til 173 kilotonn indirekte CO_2-utslipp. Noen tilnærminger for å redusere etterspørsel og øke gjenbruk og gjenvinning blir også diskutert.

keywords: industrial ecology, material stock analysis, circular economy, urban mining, steel, building materials, climate change, material flow analysis, waste management

Contents

List of Figures

List of abbreviations

BIM - building information model

CE - circular economy

EPD - environmental product declaration

GHG - greenhouse gases

GIS - geographic information systems

IPCC - intergovernmental panel on climate change

LCA - life cycle assessment

MFA - material flow analysis

MI - material intensity

MSA - material stock analysis

UFA - useful floor area

SFH - single family house

MFH - multifamily house

AB - apartment building

1 Introduction

1.1 Motivation

According to the IPCC, human actions have caused a 1 °C increase in global temperature since the industrial age, with an expected further increase of 1.5-2 °C if the current situation persists (IPCC, 2018; Rabani et al., 2021). Therefore, reducing GHG emissions in the present and future is highly prioritised in the global community, as seen through the commitments made by most countries in the Paris, Copenhagen and Kyoto agreements (IPCC, 2018).

However, the development of the built environment puts pressure on the environment and threatens climate change mitigation. The building sector accounts for 25-40% of global emissions (World Economic Forum, 2016) and is the world's largest consumer of raw materials (Pomponi & Moncaster, 2017). Projections show that the inflow to the global building stock is set to increase; building floor area is expected to double by 2060, with 230 billion m^2 (Architecture 2030, n.d.), due to a growing population and change in lifestyles. The services tied up in the built environment are fundamental to human well-being; it provides residence and enables the transport of goods and people (D. Muller, personal communication, 2022). As seen in Figure 1, the development level of a country (here, GDP is used as a proxy) is often strongly tied to the size of the built environment.

The demand for resources in the built environment comes from the need to create and maintain stocks, which provides the service (D. Muller, personal communication, 2022; Cullen et al., 2012). However, as the stock itself provides the resource, it should not purely be seen as determined by the inputs and outputs, but as a driver of these flows (Augiseau & Barles, 2017; Müller, 2006). Currently, the socio-economic metabolism[1] is not sustainable, with almost all societies increasing their building stock, especially developing countries. This requires an enormous amount of resources and could be detrimental to mitigating climate change, exacerbate resource shortages, put stress on land and water, and produce waste.

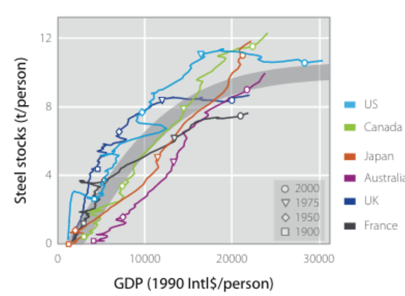


Figure 1: Steel stocks in-use against GDP for different countries. Reprinted from Allwood and Cullen (2012).

The building stock globally is primarily made up of four main materials: concrete, steel, timber, and masonry. Material production is resource-demanding, and together with energy use and transport, emissions from materials contribute to the fact that the building sector accounts for 40% of global GHG emissions.

[1]"the set of all anthropogenic flows, stocks, and transformations of physical resources and their respective dynamics assembled in a systems context" (Pauliuk and Müller, 2014, p.132)

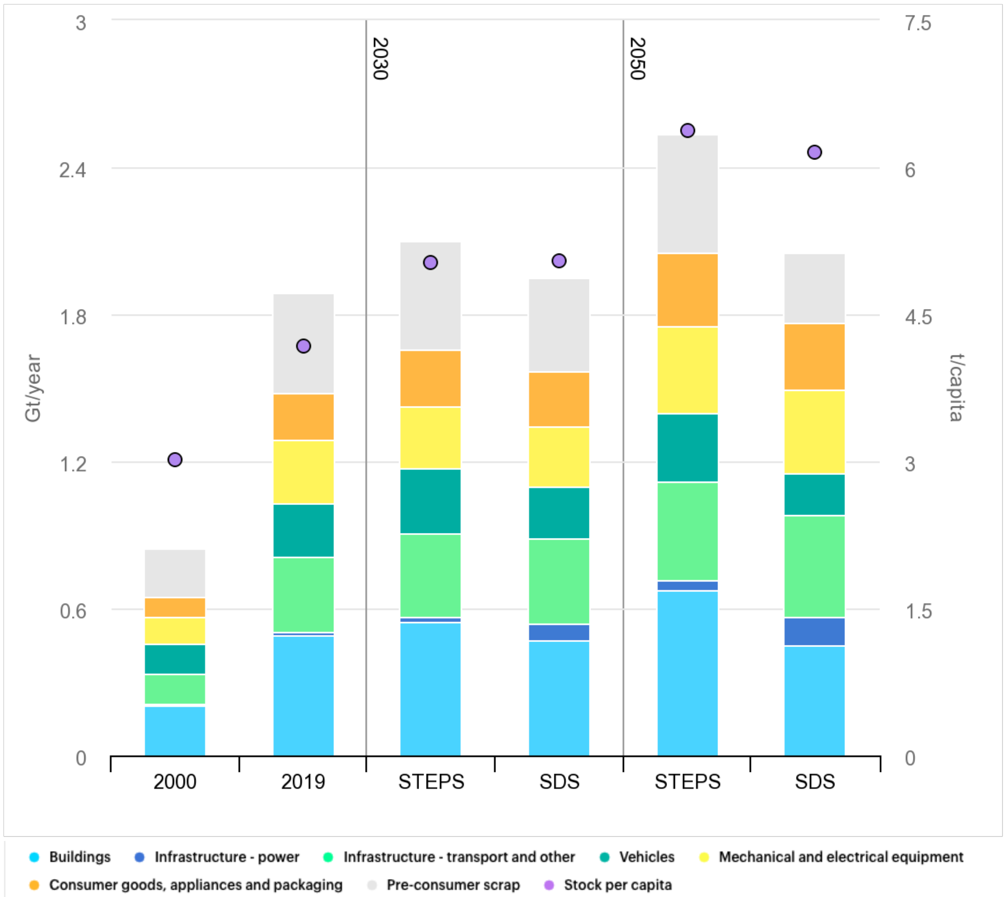


Figure 2: Global end-use steel demand and in-use steel stock by scenario (STEPS = Stated Policies Scenario, SDS = Sustainable Development Scenario), 2000-2050. Reprinted from IEA (2020).

Steel is essential to the building stock and has become an important building material in recent decades. In 2020, almost 1900 million tons of steel were produced, a tripling of the production rate 50 years ago (Conte, 2021). Around 44 % of this ends up in buildings, and 14 % in infrastructure (Allwood & Cullen, 2012). Furthermore, the use of steel will increase in other sectors. It will be fundamental to the energy transition for solar panels, wind turbines, and electric vehicles (IEA, 2020). Figure 2 illustrates the possible future demand for steel.

It is essential to keep the resource available. However, producing steel has many environmental consequences, from the energy and carbon-intensive transportation to the waste created. Overall, the steel industry contributes to about 8% of global GHG emissions and accounts for 7% of the final energy demand (IEA, 2020). Due to society's dependence on steel, as well as the environmental impact of producing it, it is essential to study steel and discuss its uses and potential. This thesis focuses on the building stock, as this is a sector where the material is widely used. Furthermore, the building sector represents essential opportunities in terms of circular economy and urban mining.

To reduce these harmful consequences while still providing the services of the built environment, the concept of circular economy (CE) will be fundamental (Pomponi & Moncaster, 2017). The principle of CE is better management of resources by closing loops. This is done by reusing resources seen as waste in the linear economy, as well as slowing these loops (Leising et al., 2018). The concept has gained recognition and momentum in academia, business and politics. However, the knowledge and tools for it being used in practice are still lacking (Leising et al., 2018; Mohammadiziazi & Bilec, 2022), despite the current building stock representing a significant source for the future supply of resources (Kleemann et al., 2017). This is especially true for the building sector, where innovation happens slowly (BIS, 2013). Furthermore, for the building industry, urban mining is a concept that has considerable potential. Urban mining is the exploitation of the material stock found in the built environment. Ideally, this will be material found at the end of its lifetime, which would traditionally end up as construction and demolition waste (Aldebei & Dombi, 2021). Closing loops will reduce demand for virgin materials and the associated emissions, reduce the materials' environmental impact over the total life cycle, and prevent waste from ending up in incineration and landfills.

When considering the environmental impact of the built environment, the operational emissions are often concentrated on, rather than the embodied emissions. The embodied emissions is the carbon footprint of the building (or component) before it becomes operational. This includes the production, transport and construction. In the EU and Norway there has in recent years, been a great focus on reducing energy use in the building stock, the operational emissions. There has also in research discussions been a focus on energy consumption rather than resource efficiency and embodied emissions (Ortlepp et al., 2016).

To make the tailored policy and make materials accessible for future urban mining, it is fundamental to have an overview of the resources (material quantities) and available stock (Aldebei & Dombi, 2021). Characterization of building stocks in terms of spatial and temporal aspects equips stakeholders and policymakers with information about the quantity and composition of construction materials and waste flows, which enables them to proactively address environmental concerns and take appropriate actions (Tirado et al., 2021). For waste management, results from MFA can be utilized to estimate the need for storage, treatment, and recycling facilities to reintegrate waste into the economic cycle, or for planning purposes for reusing components (Miatto et al., 2019; Mohammadiziazi & Bilec, 2022). Furthermore, it can help to give insight into where materials are most densely used.

1.2 Background & literature review

In this section, an introduction to some of the relevant literature about steel, building stock modelling and related emissions is given.

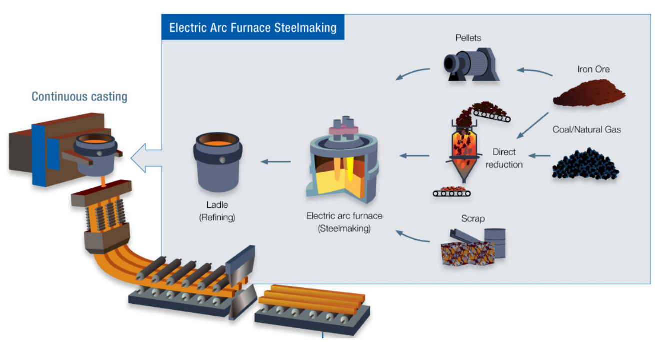
1.2.1 Production process and environmental impact

In 1855, Henry Bessemer patented his steel-making process (Allwood & Cullen, 2012), which revolutionized access to the material at an industrial scale. Today, steel is primarily produced in two ways. Either by first using a blast furnace and then a basic oxygen furnace, often used to create virgin steel, or an electric arc furnace, often used for recycling steel scrap (Eurofer, 2020). In the blast furnace, raw iron ore is combined with limestone to remove impurities, and carbon is used as a reducing agent. This is necessary, as iron ore is an iron oxide. The most common form of carbon used in the steel industry is coke, made from coal. When the carbon reacts with the oxygen, CO is produced. Therefore, the production of CO_2 is unavoidable in this production process, and production has already been optimized within the thermodynamic limits of the process (Eurofer, 2020). The coke also serves as fuel for the blast furnace and produces the necessary heat for smelting the iron ore (about 1500 °C). Next, the liquid iron is combined with small amounts of steel scrap (about 13.5-25 %) (Reed, 2023). Then the temperature is raised by blowing in pure oxygen, which makes the scrap melt, and the impurities oxidize and evaporate. This is the most common way to produce steel globally, with about 70 % of the global production, or 60 % of the European production output (Eurofer, 2020; Norsk Stål, n.d.).

In electric arc furnaces, high-current arcs from graphite electrodes with a temperature of up to 3500 °C melt steel scrap, which can form up to 100% of the steel. Other ferroalloys can be added to make i.e. stainless steel (Reed, 2023). Then, oxygen, lime and fluorspar are added to purify the steel. Around 30% of the global steel is produced in this way, or 40% of the European market (Eurofer, 2020; Norsk Stål, n.d.).

After the steel is produced, it is cast and rolled into the final products intended.

(a) Blast furnace



(b) Electric arc furnace

Figure 3: Two methods of steel making. Reprinted from Eurofer (2020).

There are several environmental consequences of producing steel. This first occurs when the iron ore is extracted from open pit mines. Equipment operation can lead to CO_2, N_2O, and SO_2 emissions (Olmez et al., 2016). The creation and work in the pits themselves also cause local impacts on ecosystems through pollution of water and air, noise, traffic and loss of habitat (Haddaway et al., 2019). Then the iron ore must be transported, inevitably leading to CO_2 emissions. However, the most significant part of the emissions by far come from the processing of iron ore or scrap steel, which was described above. In the production process, coal coking must be performed, producing methane, a highly intensive GHG (Olmez et al., 2016). It also produces contaminated wastewater (Haddaway et al., 2019). However, this is usually filtrated. Furthermore, CO_2 is produced in the blast furnace due to the chemical reaction. To operate the machines, as well as for the casting, shaping, rolling, and fabrication, fuel (mostly coal) and electricity are needed. Lastly, the production process generates sulfur dioxide, slag, and dust (World Steel Association, 2021). Overall, the steel industry accounted for 7-9% of all fossil fuel-based $C0_2$ emissions, equating to 3.3 billion tonnes of CO_2 in 2018 (Hall, 2021). The 'primary' route, which produces steel from iron ore, has an emission intensity of 1.98 t CO_2/t steel, while the secondary route generates 0.37 t CO_2/t. This is due to the different production processes and inputs. Clearly, the scrap method is preferable from an environmental perspective. However, as, discussed, it is not as commonly used. Today, the average direct CO_2 emissions intensity of steel production is 1.4 t CO_2/t (IEA, 2020). According to the IEA (2020), the steel industry must reduce its total emissions with 50 % by 2050, and the emissions intensity must decrease with 60 %, to 0.6 t CO_2/t if climate change mitigation goals are to be met.

1.2.2 Global steel cycle

To tackle the issues previously described, it is first necessary to get an overview of the steel stocks and flows to find the potential mass for recovery, the current recycling and waste rate, and where there are potentials for reduction of emissions. There have been several studies that attempt to quantify steel demand and stocks on a global or regional level, most often top-down with the use of production data, such as Hatayama et al. (2010), Müller et al. (2011), Pauliuk, Wang, et al. (2013), and Wang et al. (2007). A comprehensive overview was done by Cullen et al. (2012), partially based on the work previously mentioned. Their results can be found in Figure 4.

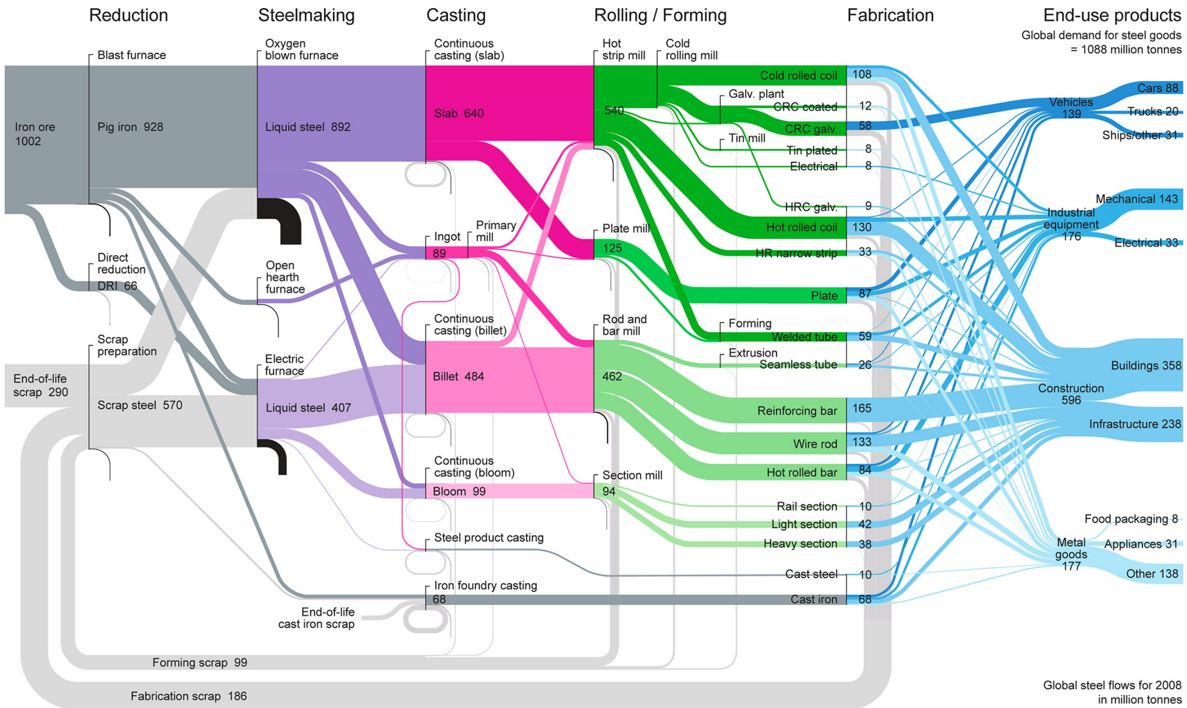


Figure 4: The global steel cycle. Reprinted from Cullen et al. (2012)

As illustrated above, there are many sectors that depend on steel products. However, the biggest consumers are buildings and infrastructure. It also becomes clear that these sectors depend on many types of steel. Furthermore, the steel scrap comes not only from the end of use but also from the fabrication and forming process, suggesting that this could be reduced by having more efficient processes.

In Norway, steel used in buildings has been studied mainly in the context of waste. Bergsdal et al. (2008) included the steel in their projections for waste from the Trondheim building stock. Here, it was found that the amount of waste would increase for practically all building materials. The statistical data from SSB (Statistics Norway) shows that metal waste has been increasing steadily for construction, renovation and demolition. However, it can also be seen that the waste from demolition has been increasing rapidly. While waste from construction and renovation can be assumed to be smaller parts (cut-offs, mistakes etc.) which are not relevant for direct reuse, the waste from demolition has been rapidly increasing. This could suggest that there has been an increase in steel outflow from buildings.

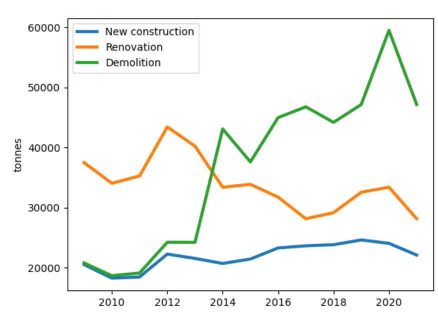


Figure 5: Metal waste from the building sector in Norway 2009-2021. Data from SSB (2022).

As for future demand, Pauliuk, Wang, et al. (2013) mapped the current and expected steel demand based on the IPCC AR3 (middle of the road) scenario, as seen in Figure 6. It was found that the steel demand will be increasing in all regions, but especially in China and India. This aligns with the development scenarios of infrastructure development in these regions. Furthermore, for some regions, like Western Europe, the scrap supply (see Figure **??** is not large enough to cover demand, meaning there still needs to be a supply of virgin steel. This shows that there should be a reduction in final demand in order to reach carbon neutrality and meet climate change mitigation goals.

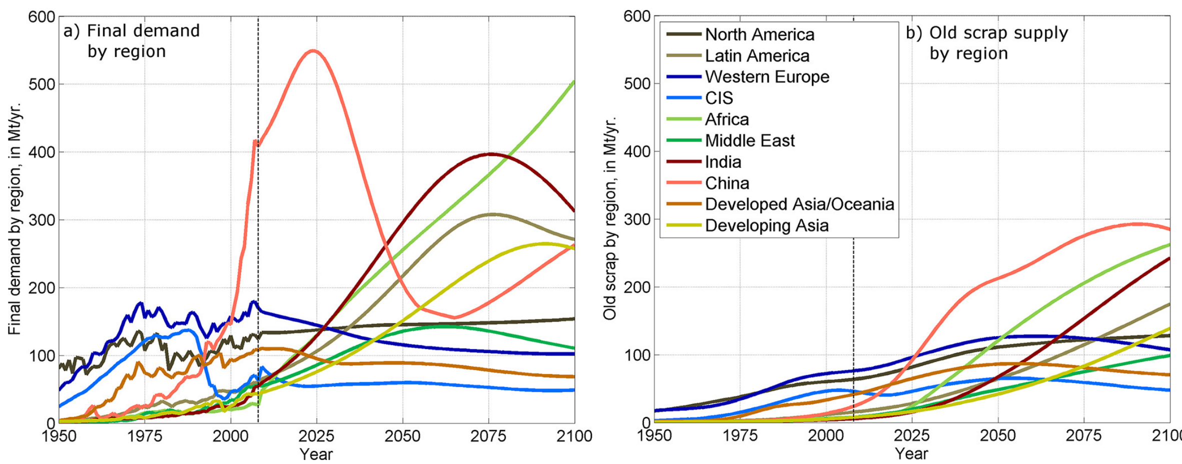


Figure 6: Final steel demand and old scrap supply by region. Reprinted from Pauliuk, Milford, et al. (2013)

1.2.3 Building stock quantification & Urban Mining

Many studies emphasise that better tracking of material composition in buildings is a key strategy for the circular economy and climate change mitigation in general (Augiseau & Barles, 2017; De Wolf et al., 2016; Gontia et al., 2018; Kleemann et al., 2017; Mohammadiziazi & Bilec, 2022; Ortlepp et al., 2016). Building stock models play a fundamental role in comprehending the potential of the building stock as a whole. In the realm of sustainability research, these models are valuable in analyzing the current, baseline, and future energy consumption of the stock, as demonstrated by studies conducted by Sandberg, Sartori, Heidrich, et al. (2016), Sartori et al. (2016), and Vásquez et al. (2016). Kavgic et al. (2010) conducted a review on the utilization of building stock models, particularly in assessing energy consumption. Their findings highlight the usefulness of these models in examining the long-term impact of energy and carbon dioxide reduction strategies. Additionally, building stock models facilitate an understanding of how the demand for buildings may evolve in the future and the subsequent implications for building material requirements, resource demand, and embodied emissions.

Additionally, Mohammadiziazi and Bilec (2022) and Tirado et al. (2021) discuss the potential of building stock models in tracking material composition and quantity in buildings, the first step in developing strategies for reuse and waste value recovery, which is key to the circular economy and urban mining. These points illustrate the need for a well-defined stock model where all aspects of the flows are well understood. In this way, policy developers and scientists can identify the most effective measures, and the construction industry could develop better strategies for renovation and new construction (Kavgic et al., 2010).

There have been several studies that have quantified building material stocks in different regions. (Mohammadiziazi & Bilec, 2022) gives an overview of the literature published on building material stock analysis (MSA), a subgroup of MFAs. Interestingly, while there are quite a few studies, most focus on one country, and only Northern America, Northern and Western Europe, China, Japan and Australia are studied in the literature. While there can be many reasons for this, such as better data availability, this shows that there is a need for studies covering the regions where there is expected more construction as a result of development, such as Africa, South Asia and South America. Furthermore, Mohammadiziazi and Bilec (2022) found that the vast majority of studies were studying more than one type of material. It was also found that several studies grouped the residential building into Single Family and Multi-Family, as is done in this study. However, Mohammadiziazi and Bilec (2022) identified that few studies incorporate building height in their studies of residential buildings, despite it being an important factor for the composition of the materials (Kleemann et al., 2017; Schebek et al., 2017). When this is not acknowledged, some resolution of the results is lost. Furthermore, Mohammadiziazi and Bilec (2022) found that distinguishing between different components is uncommon. In fact, 80 % of studies analysed materials found in both structural and non-structural components without differentiating between the two types. And, as they point out, this is crucial for planning of reuse and recycling, as there are different conditions for different components. Non-structural elements are often more often available due to their shorter (actual) lifetime and more frequent replacement, and they have fewer documentation requirements for reuse. In contrast, structural elements require more planning for reuse. Therefore, they call for future MSAs to consider building components for better planning.

There are several ways of performing material stock analyses. Most are done on a bottom-up level, while some are top-down, and a few are done with remote sensing.

Top-down models depend on available statistics about driving forces, such as population or GDP connected with data about the stock or economic or trade data (Mohammadiziazi & Bilec, 2022). This type of model for the building stock was first introduced by Müller (2006), where information about floor area per person, population and material intensity was combined. A similar approach was taken by Arehart et al. (2022), who forecast the demand for materials for building structures and its carbon emissions. While this allows for large-scale analysis due to the less data-intensive nature, it lacks the geographical aspect, so it is not helpful in locating materials. With regards to using trade data, this was done by i.e. Hatayama et al. (2010), but relies upon the availability and quality of trade data, as well as data about outflows, which is often lacking in many countries. Remote sensing, using satellite imagery, has also been used in identifying material stocks. Hattori et al. (2014) estimated the in-use steel stock by using nighttime imagery, based on the idea that stocks of materials are linked with human activity. Here, the relationship in the form of the linear regression between nighttime light and in-use stock was derived from countries where the steel in stock had already been determined and applied to countries where no such data was available.

While these methods are useful in getting a broad overview and often are quicker to perform, Mohammadiziazi and Bilec (2022) point out that these methods lack detail about location, as statistics are often only available on a national level. The bottom-up approach is based upon combining the physical attributes of the buildings (such as floor area) with material intensity, measured on a common unit and combining the result of each building (category) (Ortlepp et al., 2018). There are different ways of attaining MI data; this will be discussed in the next section. Bottom-up models have the advantage that they are able to produce results with a higher resolution, by building the model on a building level Mohammadiziazi and Bilec (2022). Additionally, this makes it possible to geolocate materials. A downside of bottom-up models is the labour-intensive process (Mohammadiziazi & Bilec, 2022).

While the residential building stock is relatively well studied, Ortlepp et al. (2016) discuss the material stocks in the non-domestic building stock, which is not often discussed in the literature (Aldebei & Dombi, 2021). This could be due to the fact that these buildings represent less of the building stock (in Norway, around 60% of the buildings are residential (Thue, 2023)), or the fact that establishing MIs for these are more difficult due to the heterogeneity of the types of buildings, leading to even more labour-intensive data work. Furthermore, for many countries, there is no official data on the non-residential building stock, meaning this often has to be estimated as well, leading to high uncertainty. However, they based their analysis of the stock in Germany, based on data from buildings from a platform where projects could be submitted on a voluntary basis and then extrapolated to the stock as a whole. Here, it was found that non-residential buildings contain a much higher more metal content than residential buildings.

Common for all of these papers is that they often discuss all the materials that exist in the buildings; very few focus on metals or steel in general. The literature review revealed that most papers do not define specific material intensities based on several aspects of the building. It is either done according to use type or time-cohort, sometimes a combination. This study aims to increase the accuracy and detail of the MIs by considering more factors than these two.

1.2.4 Material Intensity coefficients

Material Intensity is a key parameter in MSA models. It indicates the amount of one or several materials per unit of a building (Mohammadiziazi & Bilec, 2022). Common units are mass per floor area, per building, per volume, or volume per volume of building (Mohammadiziazi & Bilec, 2022). The definition of Material Intensities is often a time-consuming and laborious process, where several data sources are dependent upon (Aldebei & Dombi, 2021; Ortlepp et al., 2016). Several different methods for attaining data exist, depending on data availability and the study's goals. Often, one relies on previous literature, as well as building standards, and handbooks (Mohammadiziazi & Bilec, 2022). Otherwise, identifying the composition of sample buildings that are seen as representative can be studied by examining the inventories of LCAs, construction documents and on-site inspection. Furthermore, the use of BIM-models is useful for extracting material quantities. However, this is only available for newer buildings, as the technology is relatively new. Some studies also base themselves on expert knowledge to design archetypes, such as Marcellus-Zamora et al. (2016), Mastrucci et al. (2017), and Stephan and Athanassiadis (2017).

There are two main ways organising and attaining data; either by looking at case studies of real buildings as a part of a representative sample and its materials; such as Gontia et al. (2018) and Kleemann et al. (2017), either measured or found from building information, or defining a set of reference buildings, or archetypes; such as Lichtensteiger and Baccini (2008) and Nasiri et al. (2021) (Schebek et al., 2017). Then, the composition can be identified.

An example of the case study approach includes De Wolf et al. (2016), who studied the material quantities in structures in over 200 buildings, based on data from projects obtained from the industry in the form of BIMs. Here, a platform made specifically for this project, where companies could submit their own data, was used. The dataset included several use types of buildings, such as offices, commercial buildings, sports buildings and residential buildings. They also divided their results in terms of the structural types of the buildings studied. This study emphasised that even when industry data is available, there is no harmonised way of extracting it, due to different level of details in engineering programmes used and system boundaries, so each datapoint can be at a different level of detail. Furthermore, it was found that one structural type does not seem to be better than another one; rather, the engineers should find the best solution in each individual case. This study is one where the level of detail is high. However, it does not provide a representative picture, as the sampling was not done on a random basis. This could lead to a bias based on the types of projects that decided to hand in their data. Kleemann et al. (2017) is another study that used a case study approach. However, here the buildings that were studied were sampled. The details of how this sampling was done is not clear, however, the samples cover the different building categories that were described in their model, and Material Intensities were created based on demolition reports, on-site inspection and building documents. This information was combined with the building stock information, which allowed for a spatial distribution of the material stock when the information was added together.

For the archetype approach, one example of this is Nasiri et al. (2021) and Nasiri et al. (2023) who studied the building stock of wooden residential buildings and developed archetypes. As construction documents of many buildings is publically available in Finland, this allowed for the researcher to choose buildings within each type and cohort that were seen as representative (with a median building size of all the buildings in that category), and created BIMs in Revit of these, based on floor plans. This allows for a detailed account of materials - however, reflects the planned materials used, rather than the actual ones used. This method is also dependent on the availability of data for sampled buildings - no such platform exists in Norway, as details are not required by the authorities when submitting a building application. Furthermore, the complete modelling of buildings bottom-up is time-consuming and requires knowledge about construction (B. Nasiri, personal communication, May 12, 2023). Tirado et al. (2021) did a component-based model of the building material stock of residential and non-residential buildings on a macro-level in a region of France. The model was built upon archetypes of buildings for each use type and cohort group, as well as housing data in the form of GIS. The study considered all the cohorts present in the building stock. The result was a detailed overview of the building components that accounted for most of the building weight. Additionally, Lanau and Liu (2020) also took an archetype approach when they developed an urban resource cadaster for a city in Denmark and mapped the building stock on a geographic scale. Here, one archetype for each of the three building types was defined for 10 cohort groups, based on a previously defined typology for energy refurbishment renovation. They built the building inventory by randomly selecting buildings and analysing architectural and technical records that were stored in the national building archives. When there was not enough documentation, the definition was based on assumptions based on historical construction techniques and building regulations.

Gontia et al. (2018)'s paper on Material Intensities in the Swedish building stock has been influential in the field, as it provides one of the most comprehensive and detailed overviews of the MIs in the residential building stock, not only for a country or building type, and it was the first of its type in Europe. Here, a case study was done on 12 SFH and 34 MFH, which had previously been studied with the aim of better understanding the architectural history of Sweden, and for which the material data was available. Specific buildings were chosen as representative buildings for each type-cohort, based on analysis of real estate advertisements, plans, interviews with historians and on-site pictures. Then, the volume of materials was multiplied by its density, making it possible to study the material intensity of the different types of buildings.

Lederer et al. (2021) criticised the aspects of the approach of studies such as Kleemann et al. (2017), where samples of 'representative buildings' were chosen, based on the fact that sampling is not done in a truly representative or random fashion (Ilgemann, 2023). They acknowledge that this is often done due to data availability. Therefore they attempted to do this for a random sample of 1% of the buildings in Vienna. However, this had to be adjusted to 0.1 % due to the sheer size of buildings that had to be analysed. In the end they found that the results differed significantly from those of earlier models studying Vienna, arguing for a random sample approach.

Hart et al. (2021) has taken a different approach to data collection, by generating 127 designs of structures of buildings based on based on UK building codes and random sampling of building sizes. Here, they developed total materials for different types of structures and its embodied emissions. While the results in this study were not used to calculate a total stock, it represents an input to archetype models.

Ortlepp et al. (2018) discuss a general problem with the Material Intensity factors applied in the literature: overly generalized coefficients. The result of this is a poor reflection of the diversity of materials. This could be due to the researchers taking into account only construction type without considering use type, or only considering the building size. When these typologies are applied, they are often quite general. While this generalisation allows for studying more building, it leads to a poor resolution of the result. Additionally, their usability for future research depends on the system boundary of the study. If the study considers the material intensity per cohort but does not differentiate between use types, it is not transferrable to studies which do this. Furthermore, a major problem with material intensities is that they are often not transferrable to other temporal or geographical contexts, as they are dependent on many factors, such as building styles, building codes and regulations, trends, supply of material, climate conditions and temperature, geological activity, historic and economic development (Gontia et al., 2018).

1.2.5 Embodied and operational emissions

The building stock contributes to climate change in two main aspects; materials and energy use. When we discuss emissions and energy use for buildings, there are two main types we look at. The first is embodied emissions, which are associated with the production of materials, constructing and maintaining the building, and occurs at the start of a building's lifetime (Arehart et al., 2022). The other is operational, which pertains to the energy use of the building, and is distributed over the lifetime of the building (Arehart et al., 2022).

There has been a strong focus on making the building stock more efficient in terms of energy use for heating, cooling and other use (Sandberg, Sartori, Heidrich, et al., 2016; Sandberg, Sartori, Vestrum, et al., 2016; Tuominen et al., 2012). This is supported by EU's regulations on energy use for new buildings as well as for renovation (EU, 2012). As the building stock is characterized by a long lifetime, it is seen as essential to upgrade the buildings that already exist. Generally, newer buildings use less operational energy than new ones, due to more stringent regulations when it was built. However, it is often possible to upgrade a building to higher standards by renovation. With the EU's goal of -60% emission reduction by 2030 and climate neutrality by 2050, this is necessary (European Commission, n.d.).

Allwood and Cullen (2012) discuss that in recent years, the industry has been successful in reducing operational emissions through the many methods of making buildings more energy efficient. This includes better insulation, changing windows, balanced ventilation and so on. The building of 'passive houses' or 'net zero' buildings shows that we are well on our way to improving this. However, the impact of embodied emissions has been relatively steady and might soon become the larger part of the emissions (Allwood & Cullen, 2012). Furthermore, Reyna and Chester (2015) discuss how not properly understanding the embodied emissions in the building stock can lead to a lock-in effect [2]. While it is possible to adjust operational emissions after the building has been constructed through renovation or behavioural changes, the embodied emissions are irreversible (Sandberg et al., 2017). This is especially

[2] The lock-in effect is committing oneself to a pathway that is difficult to diverge from (Chester et al., 2014)

relevant due to the long lifetime of buildings (in Norway, it is often assumed to be 60 years, but it can also be much longer). It is therefore important that the embodied emissions are studied in order to better plan for future buildings. This shows that there is a need to focus on embodied emissions, as this thesis does.

Generally, there is in the literature not a large focus on material use and its impact. This could be explained by a general idea that the operational emissions are in general a larger part of the building's total lifetime emission (Lausselet et al., 2021), as well as the lack of data for these types of models. Lausselet et al. (2021) discuss the importance of considering embodied emissions, as well as Material Efficiency, the idea of providing material services with less material production and processing. As they point out, not much work is done on the role of ME strategies and building-specific decisions.

1.2.6 Circular economy

The EU's waste hierarchy (as seen in Figure 7) provides a framework for priorities regarding the handling of waste/materials in order to implement a circular economy into society. Here, the prevention of production takes first priority, then reuse, recycling, recovering, and disposal is the last resort. This hierarchy provides a framework prioritisation in policy and in terms of potential for emission reduction. Generally, recycling refers to the recovery of waste material by reprocessing it into new products or material which serves the original or another purpose (European Council, 2008). Downcycling refers to recycling that results in the new products being of lower functionality and quality than the original, while upcycling refers to the opposite (Helbig et al., 2022). Reuse generally refers to the direct reuse of a component without the processing that is necessary for recycling. However, the term tends to be used to cover many different processes and can refer to anything from using the product for the same or a different purpose (Cooper & Gutowski, 2017).

Figure 7: The waste hierarchy. From Directorate General for Environment (n.d.)

1.3 Research gap & research question

The literature review has uncovered several research gaps. First, as discussed, there has in the literature and policies been a focus on operational emissions rather than embodied emissions, and this is something that there is generally a lack of data on. There is also little focus on material efficiency, and the pathways which could be taken to reduce final demand for building materials. Furthermore, as Material Intensities and building types are often different by region, studies on the composition of the building stock should be done on a regional level, and data specific to Norway should be applied to a model of the city's stock. This study aims to increase accuracy by doing this. Additionally, MSAs are often performed on an aggregated level, for the whole building, or even for a whole building type as a whole. This makes it difficult to understand the stock on a component level. Lastly, Mohammadiziazi and Bilec (2022) pointed out that analysis of material stocks on a component level is currently lacking in the literature. This model addresses this gap, and, combined with focusing on only one material aims to increase the resolution and accuracy of the analysis. In order to better plan for efficient urban mining, it is necessary to get an insight into which components are most steel intensive, both in absolute and relative terms and in which types of buildings have a high potential for harvesting steel resources. This also applies to the considerations which should be considered with regard to the reduction of materials used in new buildings.

Therefore, with a novel method which aims to increase the resolution in result, not only considering type of building and cohort, but also the aspects of structural type and components, this thesis aims to explore these research questions:

- "Where and in which components can steel be found in the Trondheim residential building stock, and what does it amount to?"
- "What are the indirect emissions of steel in the building stock, and where is there potential for reducing these emissions?"

2 Methods

The methodology of this thesis is based on Material Flow Analysis (MFA) and the theory of understanding stock dynamics, as outlined in Brunner and Rechberger (2017) and further described in Bergsdal et al. (2007), Lauinger et al. (2021), and Müller (2006). MFA is an essential method for understanding the sustainability and services the building stock provides to society and has been identified to be essential for defining circular economy strategies (Brattebø et al., 2009; Tirado et al., 2021).

As mentioned in 1.2.3, top-down models are often restricted to the national scale. As the circular city project aims to study Trondheim, which is small in terms of geography, there being no Trondheim-specific trade data, it was decided a bottom-up approach be more appropriate. As the motivation is also to better plan for reuse, this also has the advantage that it is possible to geolocate the materials.

In this study, only one material is tracked (steel), rather than all materials in the building stock. Steel was chosen as it was seen as one of the materials where there is a high potential in terms of reducing embodied emissions.

The method section is split into four parts, corresponding to the three boxes in Figure 8. First, the method of estimating the structural type will be explained. Then, the method for modelling the foundation will be explained. Lastly, the final method, the building component model and the embodied emissions will be explained.

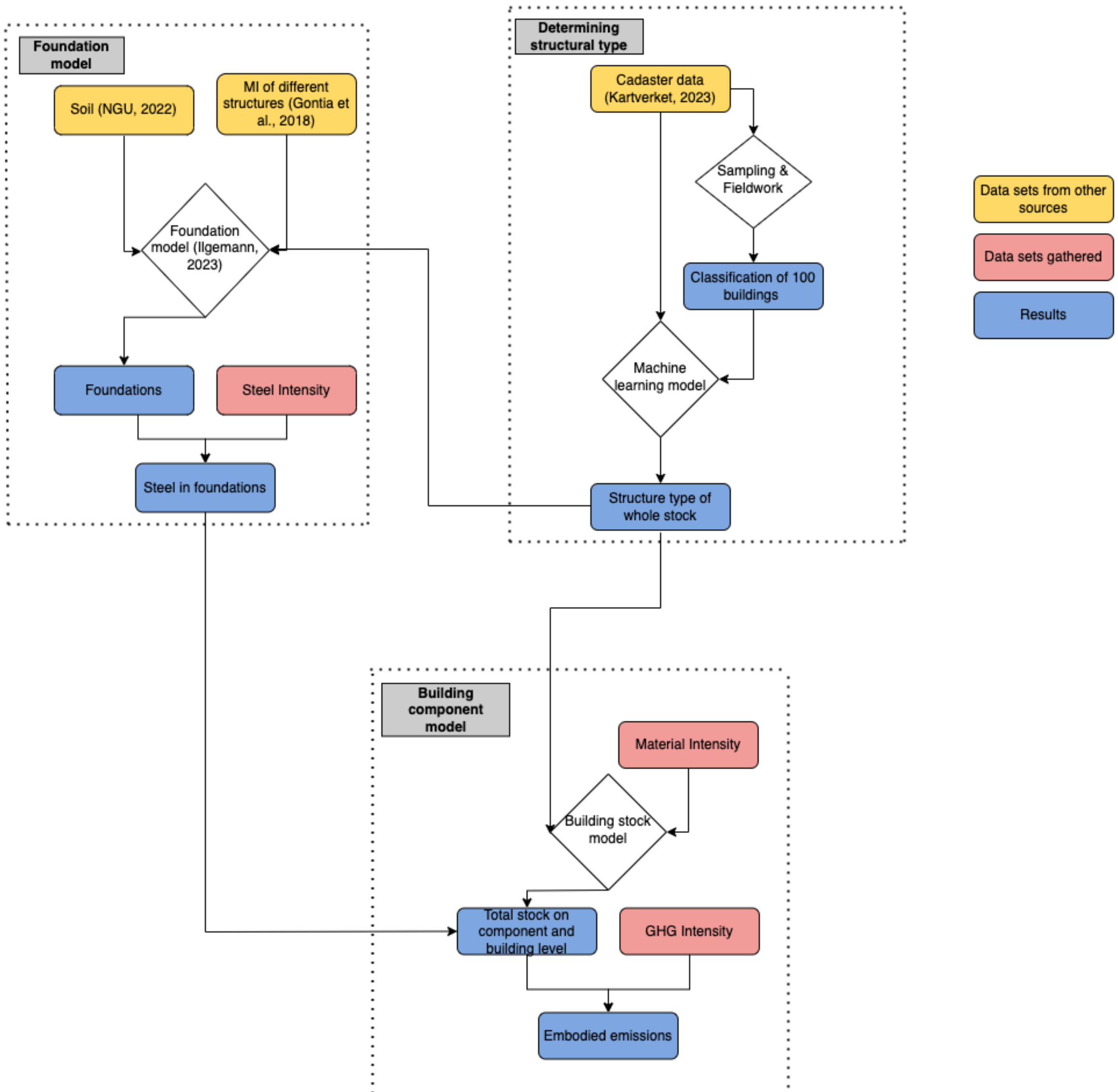


Figure 8: Overview of the methods used

2.1 System Definition

In Figure 9, a simple version of the model is shown. As the study considers the use of buildings as one process (albeit a complex one), and only considers the flows of steel, the flows are also represented simply.

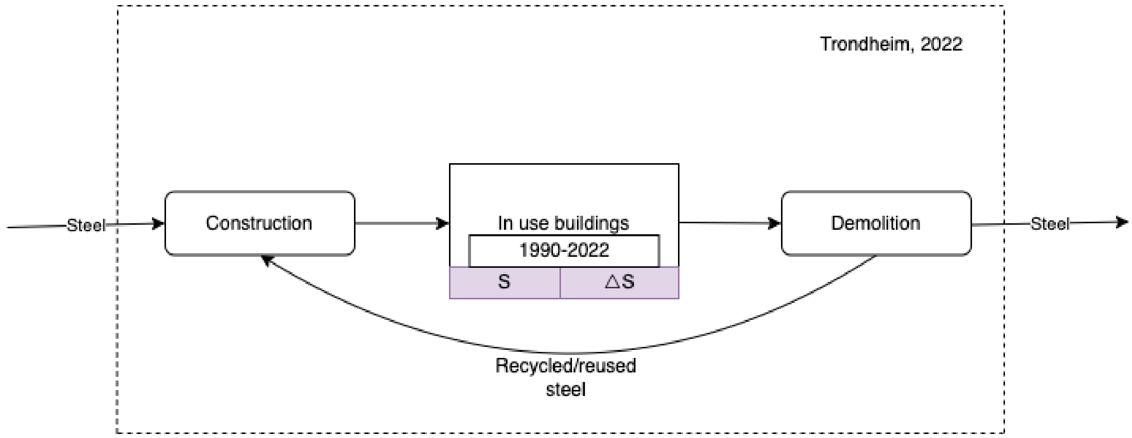


Figure 9: System

The geographic system boundary has been set to the geographic boundary of the Trondheim municipality. This is due to the availability of data (as it was sometimes necessary to perform visual inspection of the sampled buildings), and the research focus of the Circular City project, which is situated in Trondheim. The temporal system boundary is 2022, and the cohorts considered are 1990-2022. However, only buildings that have not been demolished are included in the cohorts. When studying the building stock, especially with the goal of understanding the potential outflows with the potential for reuse or recycling it is in general, useful to consider historical cohorts, due to the long lifetime of buildings. This is why past cohorts are studied here, rather than focusing on future scenarios. However, as building safety codes and building styles have changed throughout history, one cannot consider all cohorts with the same conditions. Therefore, it was decided to consider buildings from 1990 to the present, a range of 32 years. This is due to expert opinions saying that the building codes would be quite similar going back to this point (H. Dahle, personal communication, 15.02.23). Another reason for the cohorts studied was that one of Ilgemann (2023) results was that the soil type peat and bog was the most influential for the foundation volume. As Ilgemann's model (and the soil principles and building codes applied) only covered buildings built in the last 10 years, it was decided that this model should not include cohorts where building activity was higher than that. As can be seen in Figure 10, the 1970' and 80's were popular for building in peat and bog, which would require different building principles. It was therefore decided that the cohorts should cover 1990-2022.

In this model, the steel stock in Trondheim's residential buildings has been quantified on several dimensions. Firstly, the stock has been classified in terms of the cohort (construction year) and use type. Next, in Ilgemann's model, the soil type plays a large part in deciding the foundation volume. This data is integrated into this model. As a result the stock is also quantified in terms of soil type. Furthermore, as one of the intermediate results was determining the structural type, the stock is also quantified in terms of structure type. Lastly, the stock is also quantified in terms of building components, as MIs have been collected for each component type.

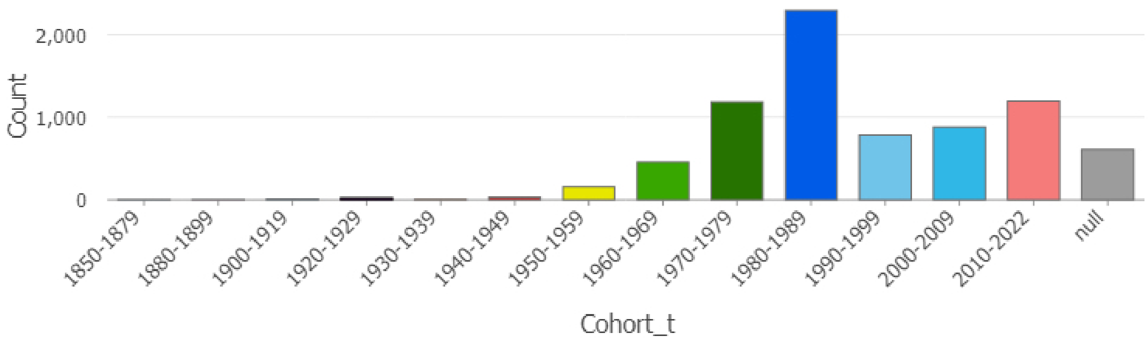


Figure 10: Amount of buildings built in each cohort in areas with peat and bog soil

So, the stock is defined as

$$S_{u,h,s,c,t}$$

Where u is use type, h is cohort, s is soil, c is building component, and t is structural type.

In this thesis, the 'stock' refers to the stock within the system boundary described here.

2.2 Data sources

This thesis is based on a bottom-up model. The input data comes from four different sources:

- Cadastre data ('Matrikkel') of the Trondheim region including localisation data.
- Data gathered from visual inspection and expert knowledge on the structural type of sampled buildings.
- Material Intensities based on construction principles, expert knowledge, literature and EPDs.
- GHG emission data, gathered from OneClick and EPDs.

2.2.1 Cadastre

The building stock data is taken from the cadastre of Trondheim, a dataset provided by the Cadastre Authority ('Kartverket'). The cadastre contains information about each building, labelled with buildingIDs. The relevant information that was extracted was the cohort ('forstedato'), the footprint size of the building, the floor area of the building, the number of floors, if it has a basement, and the use type of the building. The latter was reclassified by grouping the types into the relevant types Single Family House (SFH), Multi Family House (MFH) and Apartment Buildings (AB).

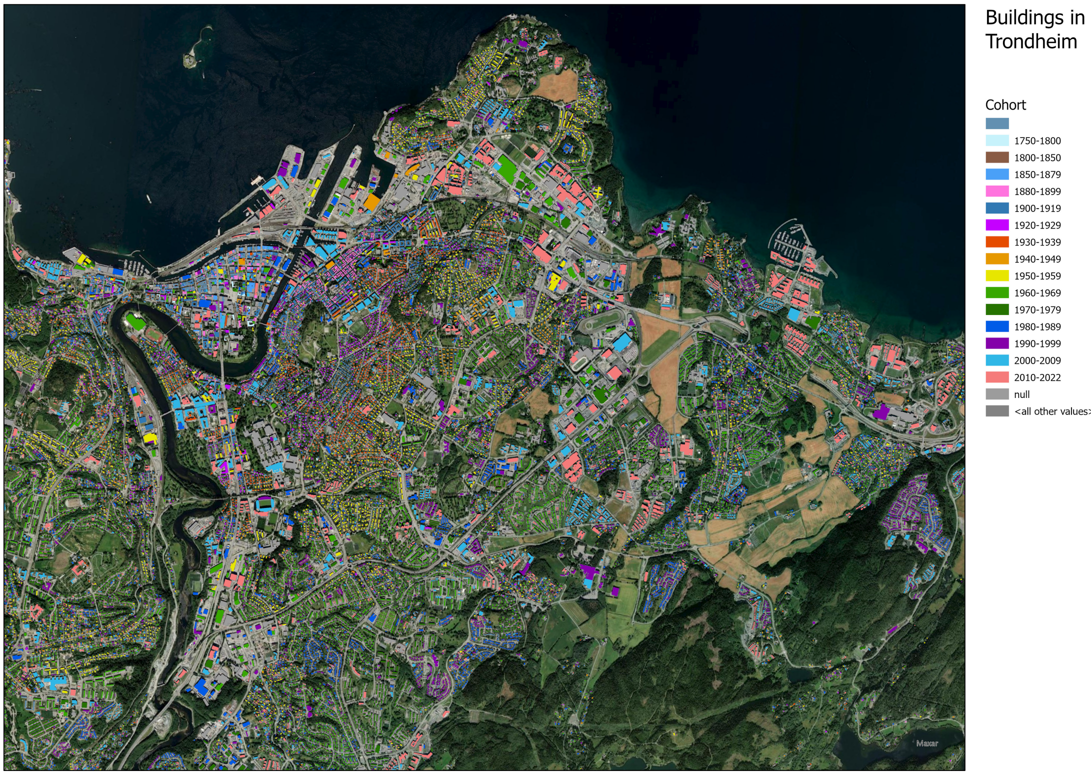


Figure 12: Cohorts of the buildings in Trondheim building stock

Trondheim is a city with a population of about 210 000, and covering 500 km^2. The building stock is made up of different types of buildings (Rosvold, 2023). The central area contains many older wooden buildings which are protected due to their historical value. However, there has also been a steady expansion of the building stock due to population growth ("Befolkningsstatistikk", n.d.). The cohorts can be seen in Figure 12.

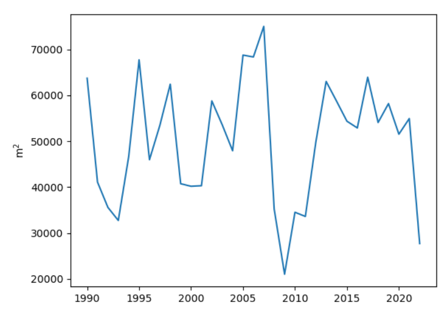


Figure 11: m^2 of floor area built per year. Data from the cadastre.

The data set, after filtering out the irrelevant buildings that were not within the system boundary, contains 10252 buildings, while the original data set was 75584. Here it is important to note that each buildingID represents a building. A building could contain several dwellings. Therefore the count of ABs will be low, so m^2 is used as a functional unit. In Figure 11, the yearly construction rate is shown.

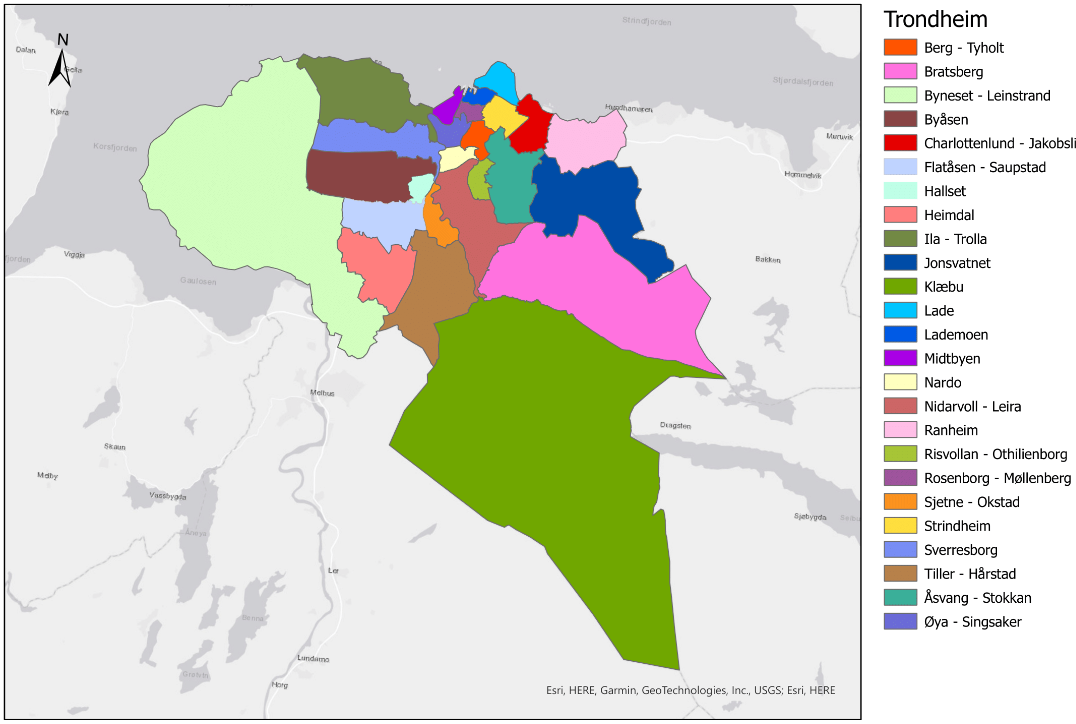
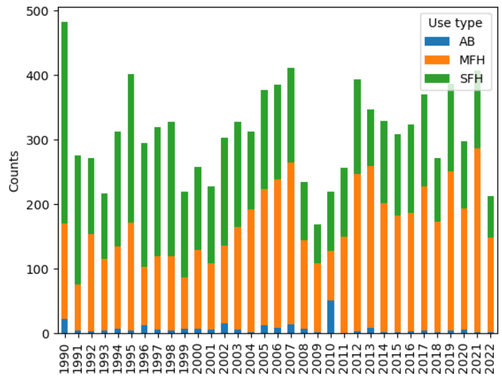


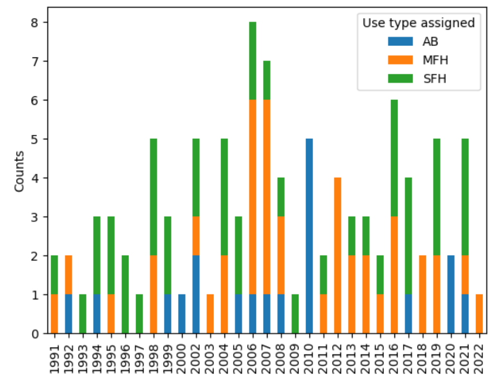
Figure 13: The different neighborhoods in Trondheim.

2.2.2 Sampled dataset

In order to be able to predict structural types, it was necessary to gather data for training the model. This was done by selecting a random sample (described below). Then the structural type was determined based on visual inspection and expert input from an architect. The workflow was as such: the cadaster did not contain any address information, but it was possible to find location information in GIS based on the sampled buildingIDs. Then, coordinates were put into Google Street View. From here, a picture of the building was collected and put into a spreadsheet. In some cases, the building was not visible on Google Street View. In these cases, I went out to the addresses and photographed it myself. Then the building was coded with a structural type. Depending on the buildings, it was often simple to judge the structural material, such as timber or masonry buildings. For others, it was less straightforward, as the cladding was the only visible part of the structure. For this reason, an architect familiar with the concept of quantifying materials gave his expert opinion on the dataset, often confirming the first judgements made by me or giving some more insight into the more complicated cases. This 'visual inspection' is a limitation of this study, as it is often difficult to judge from the surface/outside of the building. However, with the input of experts, it was seen as sufficient for the scope of this study, as the more obvious type (wood) was by far the most common type of building.



(a) Number of buildings in the Cadastre within the system boundary.



(b) Number of sampled buildings.

Figure 14: Distribution of buildings in the two datasets.

It was decided not to include a category called 'mixed/composite' due to the complicated nature of finding MIs for this category, but rather assign a category that fit most closely.

As can be seen in Figure 14a, the city is mostly made up of MFH and SFH buildings. Here, it is important to note that the sampling (see Figure 14b is not meant to be fully representative of the stock as a whole, but is meant to cover all the different types of buildings studied (described below). However, within the different categories, the sampling is random.

2.2.3 Material Intensities

As discussed in 1.2, gathering MIs is often a time-consuming effort which is often based on several different data sources. As other methods, such as obtaining or building BIMs or technical drawings or demolition reports were outside of the scope of this master's thesis due to lack of available data it was decided to gather data from several different sources. This also allowed the scope of the work to within a manageable boundary.

At first, the plan was to contact contractors who could give estimates or values from real projects. However, it often proved difficult to establish contact, and in the cases it was successful, no data was available. However, some data was gained from this method, through contact with some building engineers.

Some MIs were established based on expert information. For example, the information on ventilation and plumbing and 'other services' services was established based on information from Håvard Bergsdal, who are currently working on gathering a database with such information. As the values they provided were for non-residential buildings, it has been reduced by 50%, as it is assumed that standards for buildings are lower due to smaller sizes and less stringent regulations than those which are applied for working environments. This introduces high uncertainty, as the value is an estimation with high uncertainty, which then is adjusted.

Some MIs were gathered from supplementary data from papers which discuss MIs or LCAs which provided their inventory and were normalised for floor area, such as Hart et al. (2021).

For assumptions about lengths of beams, columns and internal walls, a tool in OneClick, Carbon Designer, was used. Here, a standard reference building according to the Norwegian standard is modelled, according to the input given to create a reference building for type of building, with a specific use type, structure type, number of floors and size. From this, the building materials were calculated, and was then normalised per m^2. This was judged as a tool that could provide data for all types, for processes that are usually built according to similar engineering principles in all buildings.

Furthermore, for prefabricated concrete elements and wooden elements, information about steel intensity was found in EPDs on EPD Norge. Here, steel content per unit is stated. If necessary, the weight was adjusted to fit the unit that was set for this component (m^2 or m^3). Information about general building components and systems, such as prefabricated wooden buildings was taken from SINTEF Certification information, which describes building components and its contents SINTEF (n.d.). For information about typical materials used in the different building types, the Norwegian typology in TABULA (Brattebø et al., 2016) was used as a decision basis, as well as information from Carbon Designer.

Lastly, if no information was available, other MI within the same component and building type was applied according to my best judgement, based on standard building styles and practices.

As mentioned in the literature review, there are two main routes to determining MIs. This method can be described to be closest to that of the archetype method.

The full table of MI can be found in Table 1 and the sources can be found in the appendix.

2.3 Determining structural types

The cadastre dataset, while containing many data points for each building, does not give an indication of the main materials of the buildings, or the structural type, as this is not something that is asked by the municipality in the building application process. In order to increase resolution and apply more accurate MIs it was therefore identified that it was necessary to find a way to give indications of this. A machine learning model, based on the statistics of the training data which was manually assigned a structural type, was used for this.

Table 1: Material Intensities (kg/m^2) (some rows are grey, as there were no buildings of this type)

	Type	Levels	Cover	Structure	Ventilation	Internal walls	Roof
Wooden	SHF	1-2	0	4.28	7.36	0	0.56
		<2	0	4.51	7.36	0	0.56
	MFH	1-2	0	4.28	7.36	0	0.56
		<2	0	4.42	7.36	0	0.56
	AB	1-2	0	4.28	7.36	1.17	0.56
		<2	3.95	4.45	7.36	1.17	0.56
Concrete	SHF	1-2	3.95	25.51	7.36	0	3.95
		<2	3.95	24.69	7.36	0	3.95
	MFH	1-2	3.95	24.49	7.36	0	3.95
		<2	3.95	25.19	7.36	0.58	3.95
	AB	1-2	3.95	24.48	7.36	1.17	3.95
		<2	3.95	25.88	7.36	1.17	3.95
Steel	SHF	1-2					
		<2					
	MFH	1-2	15.55	57.46	7.36	1.17	5.40
		<2	15.55	58.62	7.36	1.17	5.40
	AB	1-2	15.55	57.36	7.36	1.17	5.40
		<2	15.55	59.64	7.36	1.17	5.40
Masonry	SHF	1-2					
		<2	0	24.69	7.36	0	0.56
	MFH	1-2					
		<2					
	AB	1-2	3.95	24.46	7.36	1.17	3.95
		<2	3.95	25.88	7.36	1.17	3.95

The result of the sample was used as training data for a machine learning model based on Bayesian Network, a mathematical model that is centered around conditional probabilities and causal relationships between variables (Yang, 2019). In this way, information from the samples could be used as training data for the model by updating the conditional probabilities between the different attributes. Then, the model could predict the structure type of each building in the Cadastre data by using the information about the attributes the model was trained on (footprint size, number of stories, use type). An overview of the model can be seen in Figure 17. The model and Python code were developed by Nils Dittrich and Lombe Mutale and were adjusted for the purposes of this project.

It was necessary that the training data was based on a representative sample of the building stock. The workflow for the sampling was as such: first, the cadaster data was cleaned to only include residential buildings within the studied cohorts. Next, the use type of the buildings was recoded to the three types selected, Single Family House (SFH), Multi Family House (MFH), and Apartment Buildings (AB). Some buildings, like garages, were excluded from the dataset.

Due to the scope of this thesis project, it was decided that a sample of 100 buildings was an appropriate amount due to the work involved for each building. This represents a sample size of around 1% of the considered stock, which amounts to around 10200 buildings. In order to get a representative sample, the sample should be random. However, it was decided that there should be a threshold set for each sample group to have data for each category of the nodes paths (footprint size, number of stories, use type). This threshold was set to 5, except for one category, where there were not enough buildings to fulfil this category. This amounted to a list of 56 Building IDs. Then, the rest of the list was filled up with random values from the remaining BuildingIDs, until a sample of 100 was reached.

Table 2: Samples

Use type	**Floors**	**Footprint size**	**Required samples**	**Actual samples**
SFH	1-2	<100	5	7
		>=100	5	24
	>2	<100	5	5
		>=100	5	6
MFH	1-2	<100	5	18
		>=100	5	9
	>2	<100	5	5
		>=100	5	7
AB	1-2	<100	5	5
		>=100	5	6
	>2	<100	1	1
		>=100	5	7

In Fig 15, the spatial variation of the sampled buildings can be seen. The samples are spread over the whole municipality, but the majority are within the inner city.

After the sample was drawn, the next step was to manually assign a structural type to each of the buildings. This was done as described in section 2.2.2.

The structural types follow four categories of building structures defined by Thue (2023); Wood, Masonry, Steel and Concrete. As all the buildings in the model are built in the time after the introduction of reinforced concrete was introduced, is is assumed that all concrete buildings are reinforced concrete.

Figure 17 shows the factors impacting the outcome of the model; number of floors, footprint size and use type. The top nodes represent is data that is available in the Cadaster data, while the bottom node was calculated by the model. These factors in the top nodes were chosen because they were rationalised to affect the structure type. In Figure 18, the conditional probabilities of each group of buildings are given. This was used as a base for the machine learning model.

The machine learning model was applied to the dataset of the residential buildings in the system boundary. The outcome was an estimated structure type for each buildingID. This information was then used in the building component model and foundation model.

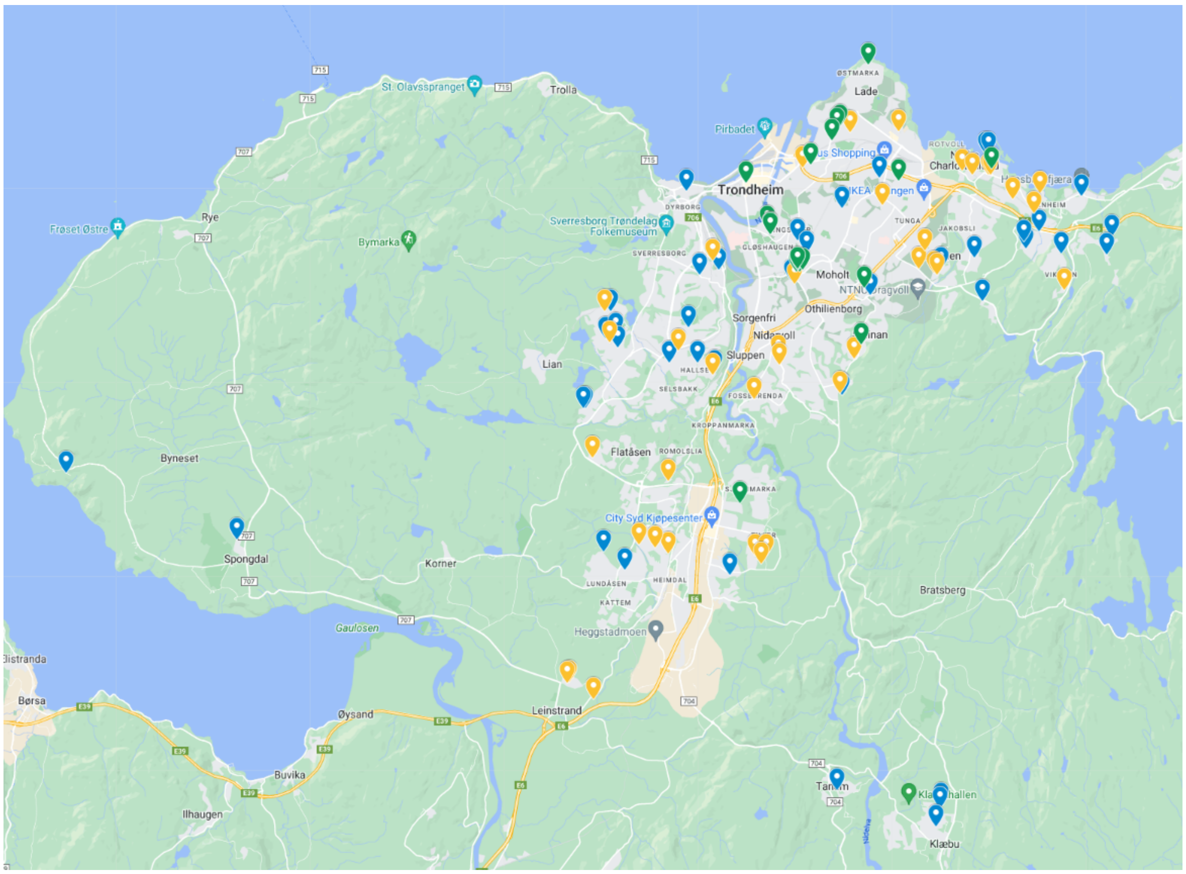
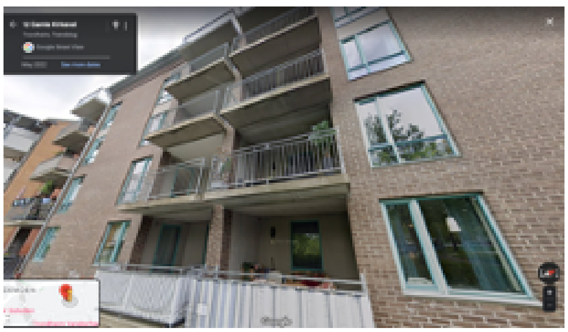


Figure 15: Sampled buildings. SFH = blue, MFH = yellow, AB = green

(a) Wooden building

(b) Concrete building



(c) Masonry building

(d) Steel building

Figure 16: Examples of buildings in the different categories

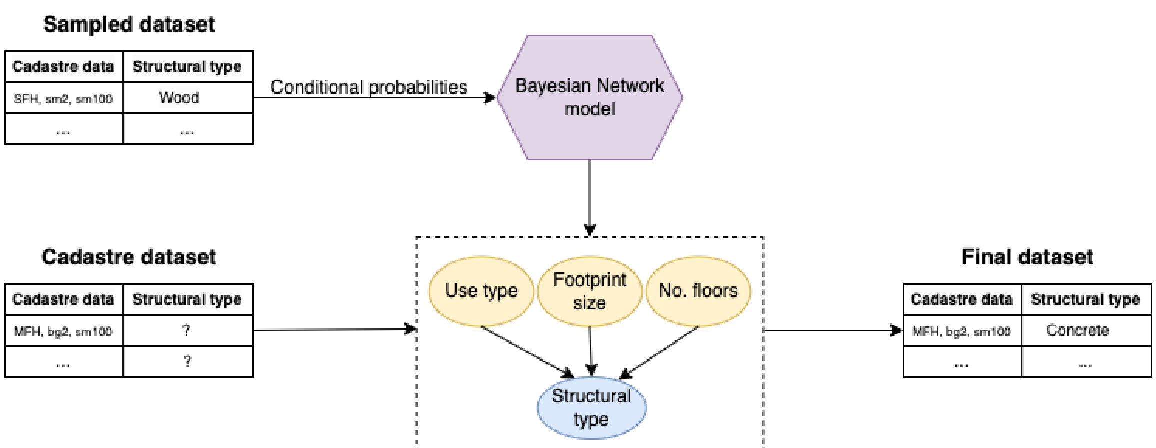


Figure 17: Overview of the Machine Learning methodology.

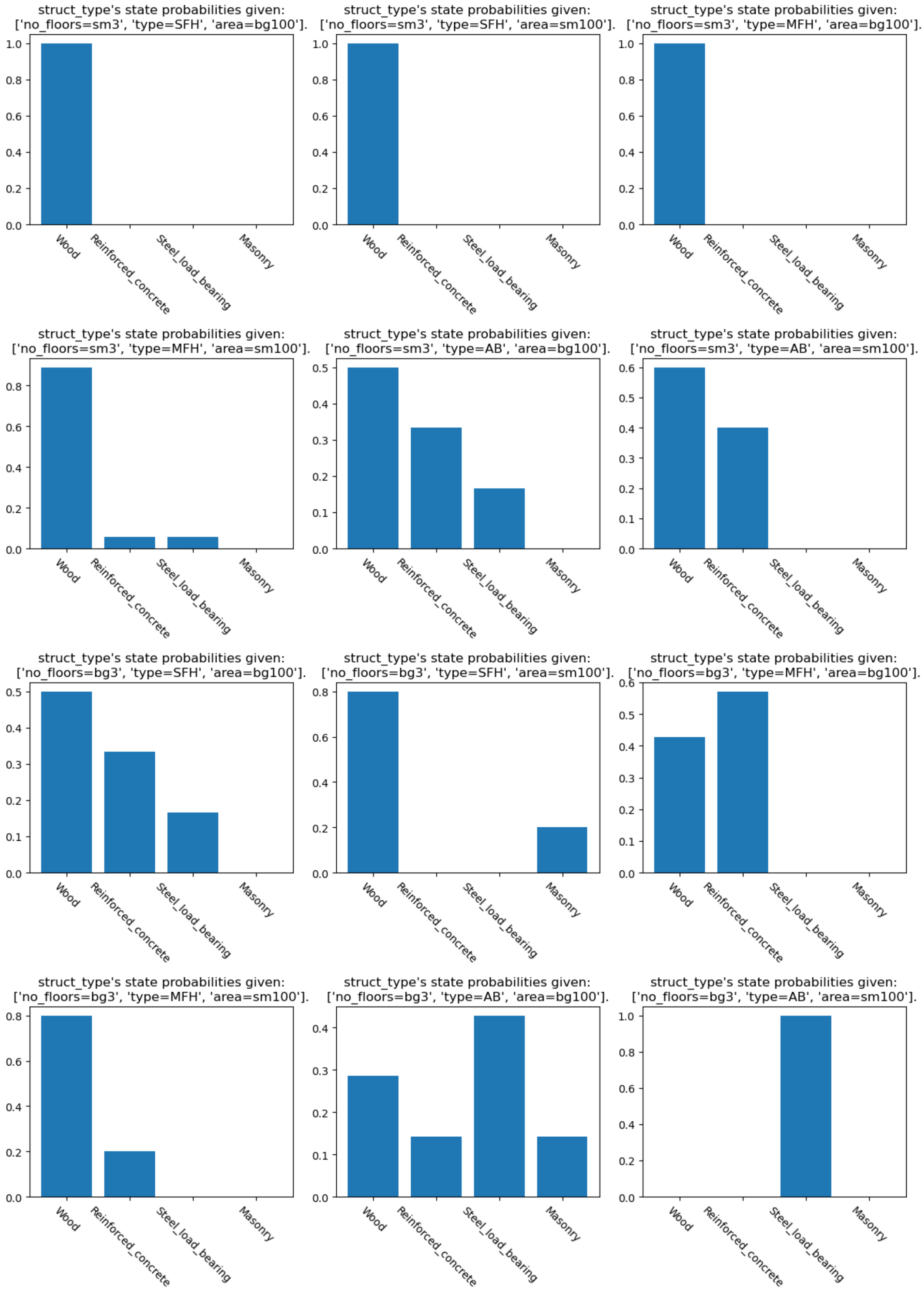


Figure 18: Conditional probabilities calculated from sampling data.

Table 3: New MIs applied. Data taken from Gontia et al. (2018))

Structural type	**New MI (kg/m2)**
Wood	157.5
Concrete	708
Masonry	984.8
Steel	672.6

2.4 Foundation model

Pablo Ilgeman's thesis focused on concrete in the foundations in the Trondheim building stock in the last 10 years. Here, the effect of soil type was considered, using functions about load bearing capacity for calculating foundation volume. A map of soil types was used, as well as the cadaster data and principles for building foundations. A more detailed account of these methods can be found in Ilgemann (2023). Foundations are in most cases in Norway made from concrete and reinforced with steel as it is necessary to withstand tension. Furthermore, it helps with waterproofing the concrete. In Ilgeman's thesis (2023), the concrete itself, embodied emissions of concrete, and transport was considered, while the reinforcement was not. It was found that the materials themselves contributed to 99 % of the emissions, while transport was the remaining 1 % (Ilgemann, 2023).

In this thesis, the model is reused with some changes. Firstly, the model's temporal system boundary is expanded from 2010-2021, to that of this model, 1990-2022, for the sake of harmonisation. Furthermore, in the original model a standard MI of $140/\text{m}^2$ for small buildings and $708/\text{m}^2$ for big buildings, based on values found in Gontia et al. (2018) was used to calculate the loads of the building. Here, as the structural type is known, a more specific MI for each type is applied. The MI is still based on (Gontia et al., 2018), both for consistency and because it is the most suitable estimate, but it now takes the structural type into account, as Gontia provided more specific MIs for the different types. One exception to this is steel load-bearing buildings, which were not studied in Gontia et al. (2018). It is therefore assumed that these are similar in MI to concrete buildings, adjusted down with 5%, based on results of Hart et al. (2021), who studied differences between these two structure types. The new MIs applied are found in Table 3

Lastly, this model accounts for reinforcement in the steel. Here, a general steel intensity is assumed for the four different types of foundations, and the volume of basement walls is estimated in Ilgemann's model. The general estimation of steel intensity is challenging, as this is something that is calculated by structural engineers based on specific loads and conditions in each case. However, some general estimates have been applied, based on available literature and information from OneClick's foundation tool. The values can be seen in Table 4.

Table 4: Reinforcement coefficient used for different foundation types

Type	**Reinforcement (kg/m^3)**
Slab	107.5
Strip footing	50.5
Spread footing	38.4
Deep pile footing	146.8
Basement	100

2.5 Building components stock model

The building stock component is based on a multiplication of the material intensities data and the Cadaster data, based on the use type of the building, structural type, and whether it is 1-2 floors or 3 floors or more. This was then merged with the foundation model outcome based on building IDs.

In an attempt to increase the resolution of the stock model, several different building components and their contribution to the total steel stock are studied. According to Thue (2023), there are six main parts to a building.

1. supporting structures, including foundations
2. the building envelope (the outer structures)
3. air conditioning system for heating, ventilation and lighting
4. room layout, furnishings and surfaces
5. system for internal transport (i.e. stairs, lifts)
6. supply system for water and sewage, electricity, telecommunications and more

In this model, part 1-4 is explored. This is partly due to data availability, as there is no way to know from the cadastre data whether the building has a balcony, for example. Furthermore, it is also assumed that in these categories, there is not much steel present, like water and sewage pipes inside the building, where the common materials are plastic and copper (Tobias, n.d.).

In Figure 19, the different components considered are illustrated. The foundation includes both the foundation and basement, if it is present in the building (as indicated by the cadastre data). The supporting structures need to resist loads in several directions: the vertical structure, which usually requires most materials and the horizontal structure, in the form of beams, which transfer the loads to the vertical structures. The structure is for simplicity represented as external walls in the figure. In between each floor there also needs to be some separation in the form of a cover, a component that separates the stories in a building, without being part of the structural integrity. This can be made from wood elements (wooden buildings), hollow concrete slabs (concrete and masonry buildings), or

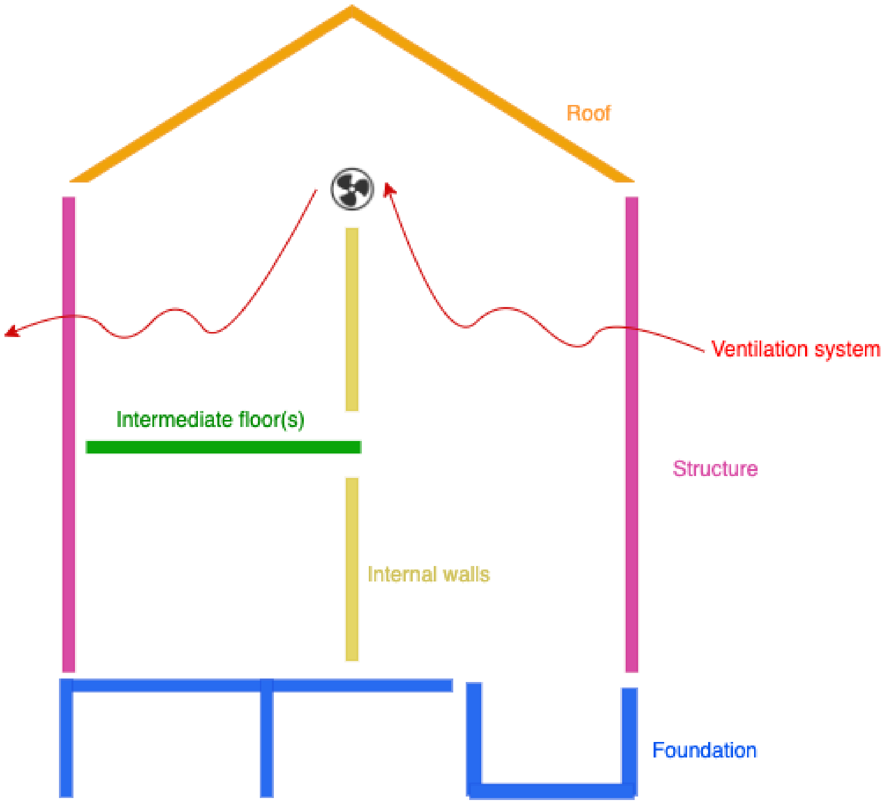


Figure 19: Building components which were considered. Based on Tirado et al. (2021), adjusted for the scope of this thesis.

composite flooring with reinforced concrete (steel buildings), and is represented as intermediate floors. There also internal walls. In this model, they are assumed to be non-load bearing, as the structure does all the load bearing. This is made from plates which are held up by stands made from concrete or wood. All houses must have some ventilation system. Here, it is assumed that all of the building types have the same amount of steel in their system, as this is more defined by use type (residential vs. non-residential) than structure type. Then, for the roof, some assumptions about the material type and structures have been made, based on archetypes. Wooden buildings have wooden elements, but these contain some steel in the form of connecting parts and plates, while concrete buildings have hollow concrete slabs and steel buildings have steel roof plates.

For each individual building the mass of steel for each component was calculated as such:

$$Foundation : S = concrete\ in\ foundation * MI_f$$

$$Structure : S = UFA * MI_{u,t,c}$$

$$Cover : S = no.floors - 1 * footprint * MI_{u,t,c}$$

$$Intermediatewalls : S = UFA * MI_{u,t,c}$$

$$Roof : S = footprint * MI_{u,t,c}$$

$$Ventilation : S = UFA * MI_{u,t,c}$$

Where u is use type, c is building component, and t is structural type, f is foundation type.

2.6 Embodied emissions

Finally, the GHG intensities are applied as the layer to the model to calculate the embodied emissions of the steel in the building components. This was done for each building by applying a specific emission intensity to the amount of steel calculated in the building stock model. The emission intensities are Norway specific, and was collected from OneClick's database and EPDs. Certain assumptions about the recycling rate of the components had to be made. This was supported by literature and information from the industry. The table of emission intensities can be found in Table 5. The emissions intensity mainly depends on the recycled content of the steel, as well as the producer and their energy supply. Here, a recycled content of 97 % for the reinforcement steel is chosen, based on communication with a foundation company, who claimed they use 100 % recycled steel (J.A. Jørgensen, personal communication, 7.03.23), while the structural steel has a 60 % recycled steel content, based data on the baseline scenario by Lausselet et al. (2021).

Table 5: Emission intensities (kg CO_2 eq./kg) (some cells are grey, as there were no buildings of this type, or no steel in this component)

	Type	Levels	Foundation	Cover	Structure	Ventilation	Internal walls	Roof
Wooden	SHF	1-2	0.5		2.3	1.57615		1.58
		<2	0.5		2.3	1.57615		1.58
	MFH	1-2	0.5		2.3	1.57615		1.58
		<2	0.5		2.3	1.57615		1.58
	AB	1-2	0.5		2.3	1.57615		1.58
		<2	0.5		2.3	1.57615		1.58
Concrete	SHF	1-2	0.5	2.7	0.9	1.57615		2.38
		<2	0.5	2.7	0.9	1.57615		2.38
	MFH	1-2	0.5	2.7	0.9	1.57615		2.38
		<2	0.5	2.7	0.9	1.57615	2.3	2.38
	AB	1-2	0.5	2.7	0.9	1.57615	2.3	2.38
		<2	0.5	2.7	0.9	1.57615	2.3	2.38
Steel	SHF	1-2						
		<2						
	MFH	1-2	0.5	0.5	2.1	1.57615	2.3	2.38
		<2	0.5	0.5	2.1	1.57615	2.3	2.38
	AB	1-2	0.5	0.5	2.1	1.57615	2.3	2.38
		<2	0.5	0.5	2.1	1.57615	2.3	2.38
Masonry	SHF	1-2						
		<2	0.5		0.9	1.57615		1.58
	MFH	1-2						
		<2						
	AB	1-2	0.5	2.7	0.9	1.57615	2.3	2.38
		<2	0.5	2.7	0.9	1.57615	2.3	2.38

3 Results & Interpretation

In this section, the results of the model will be reported. For clarity, the results are presented in three subsections. Chapter 3.1 will present the results of the model which calculated the structural types of buildings. Chapter 3.2 will present the foundation part of the model, which is based on Ilgemann's results, and which constitutes the most amount of steel. Then, the results of the building component model will be discussed in Chapter 3.3. Lastly, the embodied emissions are presented in 3.4.

3.1 Determination of structural types

The modelling of the different structural stock gives some insight to the most common structural types. Figure 20 gives an overview of the structural types of the different use types of buildings in terms of area.

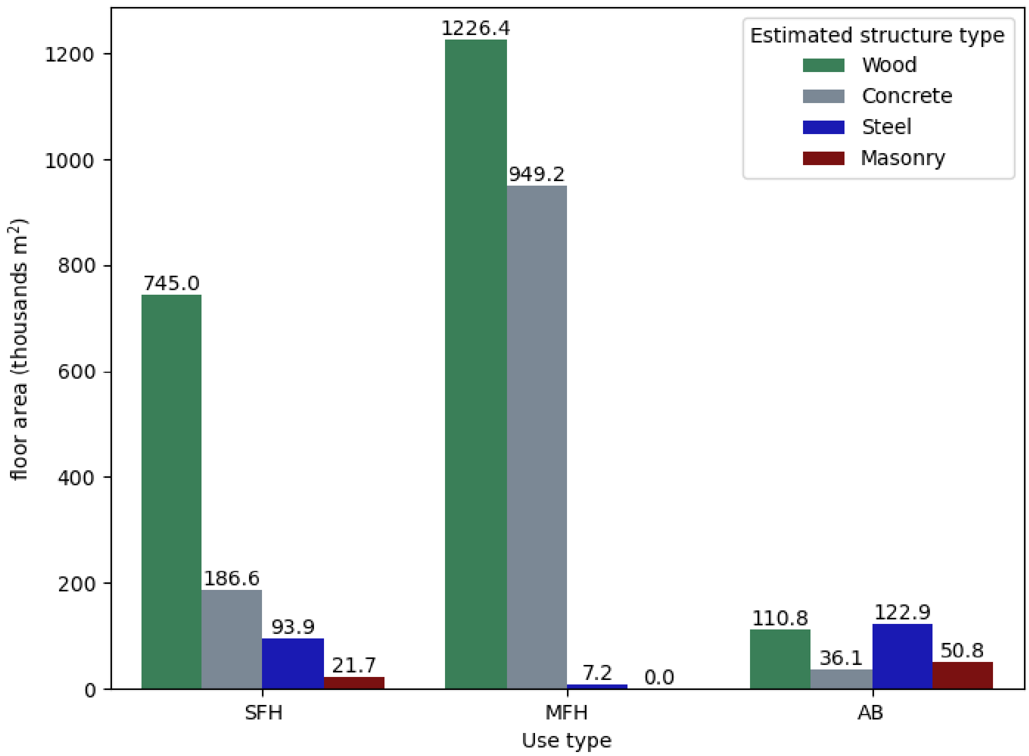
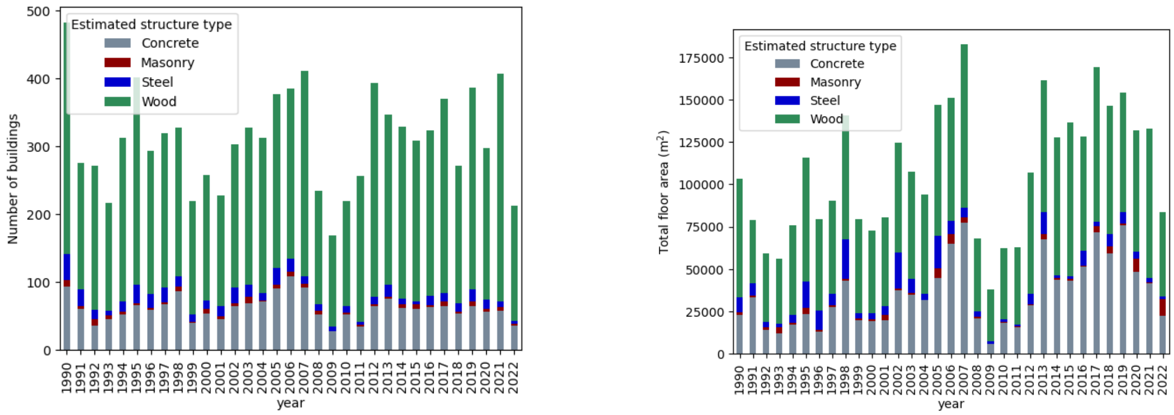


Figure 20: Intermediate results: Estimated structural types of the stock, measured per m^2.

The most common structure type is wood, accounting for 71 % in Single Family Houses, 56 % in Multi Family Houses, and 36 % in Apartment Buildings. This aligns with Thue (2023), who points out that wood is the most common type for small residential buildings. Furthermore, he points out that since the war, masonry has lost its position as a material from which one makes structures, although it is now primarily a wall-cladding material. The cohorts that were included in this study are of more recent years, so the finding here is also in line with that.

When it comes to steel buildings, this is almost irrelevant for MFHs. This is probably a result of the small sample size. It seems the ABs is the most important type of building for harvesting steel resources in an efficient manner, as this is the structure type where steel buildings are the biggest part of the total (38 %).



(a) Structural types of the cohorts, measured in counts of buildings.

(b) Structural types of the cohorts, measured in floor area.

Figure 21: Results of structural method

When one considers the temporal aspect of the stock, one can often consider each cohort as an inflow to the stock. However, the Cadaster data does not include buildings that have already been demolished. Although this will represent quite a small amount due to the oldest cohort being only 32 years old, this does not represent the 'true' inflow. Nevertheless, considering each of the cohorts' characteristics can give some valuable insight and serve as a proxy for the inflows. As can be seen in Figure 21a, the ratio of buildings of each type has been relatively constant. The total amount of buildings built per year generally follows general economic trends. For example, the economic crisis of 2008 and the next few years is easily recognizable in the drop in that and the consecutive years. However, 21b illustrates another element of this - the total floor area built decreases more than the number of buildings built in 2008. This means that the buildings built were smaller. It can be thought that when an economic crisis looms, the biggest projects are the first to get cancelled.

This trend is further explored in Figure 22, which explores the average size of each building type in each year. The first conclusion to make is that wooden buildings are in general much smaller than concrete and steel buildings. Furthermore, it seems the wooden buildings, which tend to be smaller, were less affected by fluctuations over the years, whereas concrete and steel buildings show a noticeable drop. Furthermore, it is a general trend that all the building types have increased in size over the years. This represents a general trend in Norwegian society. The UFA per person has been increasing historically (Thyholt et al., 2009). If we assume that there is the same amount of people per building, this finding is realistic.

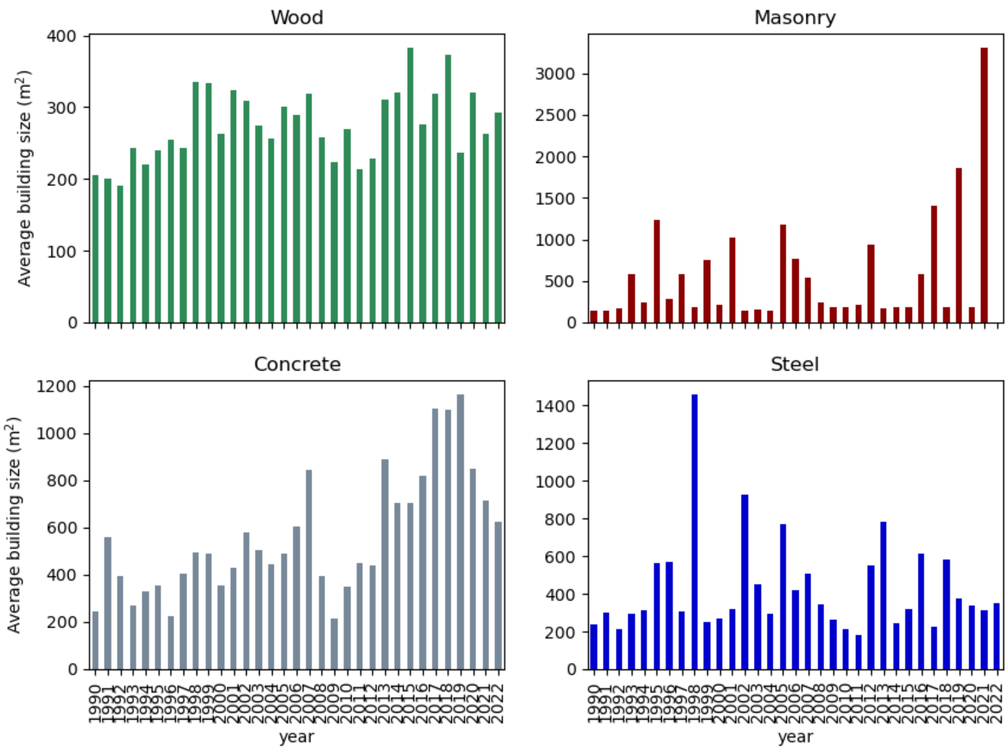


Figure 22: Average size of a building per structural type, per year.

The average floor area per building has also been analysed, as seen in Figure 22. Here, the difference between the structural types is visualised, with the wooden houses having a much lower floor area per building than the others. This is likely due to many of the SFHs and small MFHs being assigned wooden buildings, based on the sample. The average size of buildings per use type can be seen in Table 6.

Table 6: Average size of building types

Use type	Floor area per building (m^2)
AB	1308.4
MFH	408.3
SFH	224.9

As Figure 22 shows, there seem to be some extreme cases/outliers, especially for the masonry buildings. This is probably due to the low amount of masonry buildings in the sample, which translates to very few buildings in the system being assigned the masonry type. This could mean that only one building being assigned masonry can lead to a dramatic effect on the average. Therefore, this type is associated with higher uncertainties. However, for the total stock, the masonry buildings are a small part of the stock and have similar MIs to the other types of buildings, so this does not influence the result very much.

3.2 Foundations

In the second part of the model, the steel in the form of reinforcement of concrete for foundations and basement was calculated.

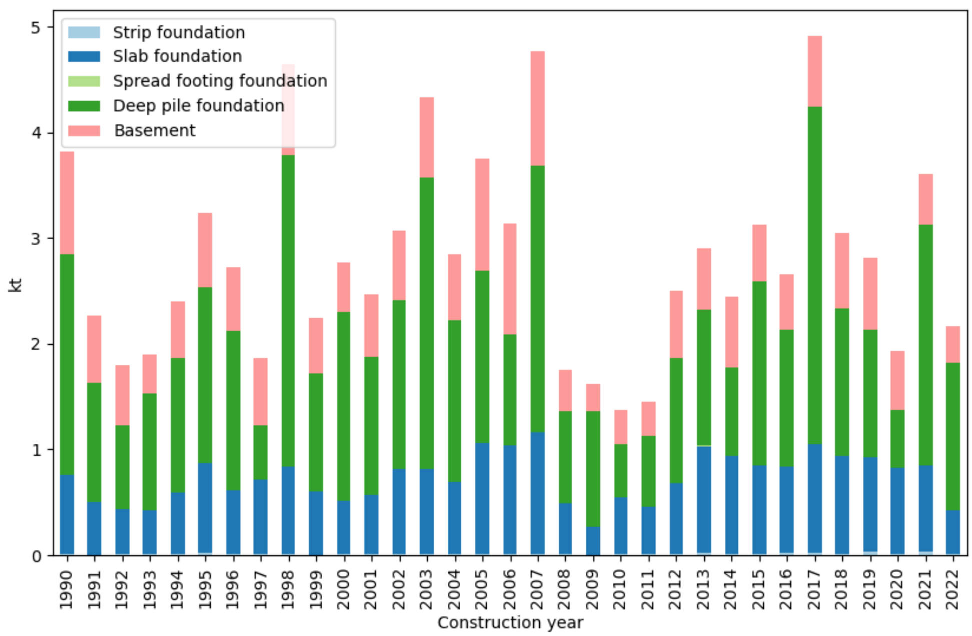
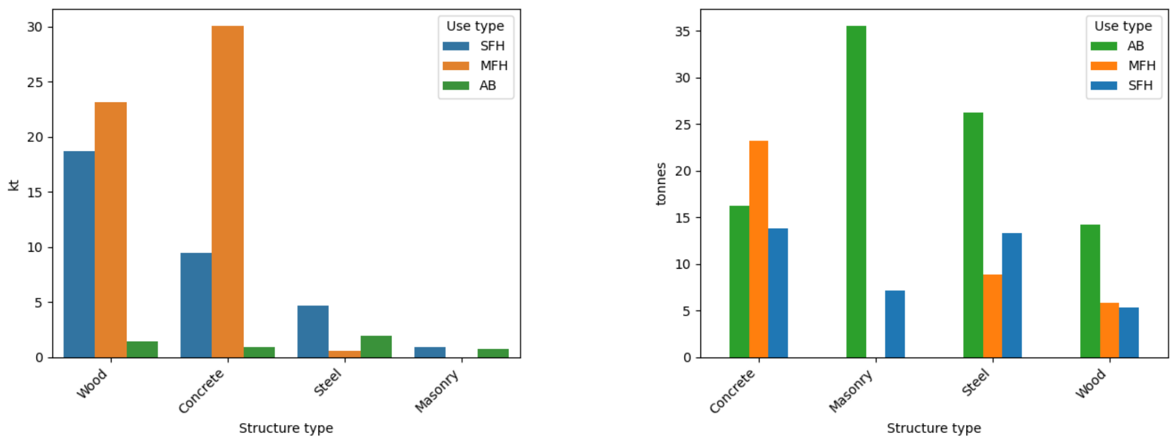


Figure 23: Foundations reinforcement by cohort

Figure 23 illustrates the total steel used in the steel building stock for the different foundation types defined by Ilgemann (2023). Table 4 shows the volume of concrete necessary as calculated by the foundation model. Due to the similar amount of reinforcement in each type, the correlation between foundation volume and reinforcement volume is high. As can be seen, the types 'Spread footing foundation' and 'Strip foundation' is barely found in the buildings, which reflects the findings of Ilgemann, where the two types of spread footing and strip footing were barely used Ilgemann (2023).

Table 7: Concrete in foundations

Type	Foundation (m^3)
Slab	220514
Strip footing	8506
Spread footing	24
Deep pile footing	325834
Basement	203983



(a) Total foundation reinforcement

(b) Foundation reinforcement per building

Figure 24: Foundation

In Figure 24a, the total steel found in the foundations is illustrated, while Figure 24b shows reinforcement per building. In this figure, the counts of buildings is used as a unit, as the results could be skewed by using area. This is because a building only needs one foundation, and it does not increase in size very much with several floors added. Thererfore, the results would be skewed towards bigger buildings, giving a lower MI of foundations per floor area for those. As we have seen that bigger buildings tend to be made of steel and concrete, this would skew the results towards this these structural types being more efficient in terms of foundation reinforcement, while it is actually a base As the total shows, there is quite there is a lot of potential for harvesting steel from wooden buildings. However, is this is in the foundation, this will be reinforcement, which needs to first be collected and remelted. While this is not as emission efficient as reuse, the scale of the total amount emphasises the need for properly dealing with waste when demolishing, making sure all materials are recycled.

The stock is also analysed in terms of location. For the foundation model, there are two factors that are important - the soil of the area of the house, and the weight of the house. Ilgemann (2023) found that peat and bog lead to the most concrete being used, and that the concrete intensity is by far the highest for areas on this soil. In Figure 25, peat and bog is shown in bright pink.

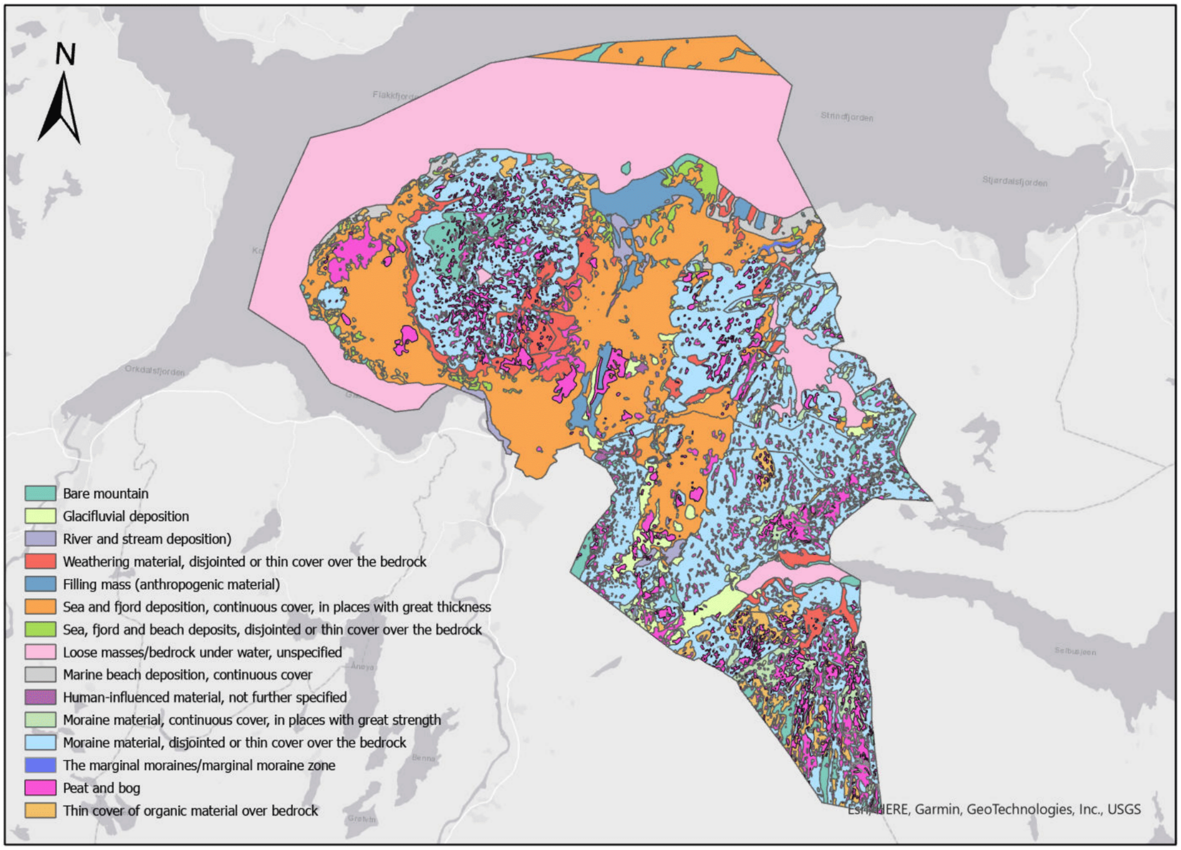
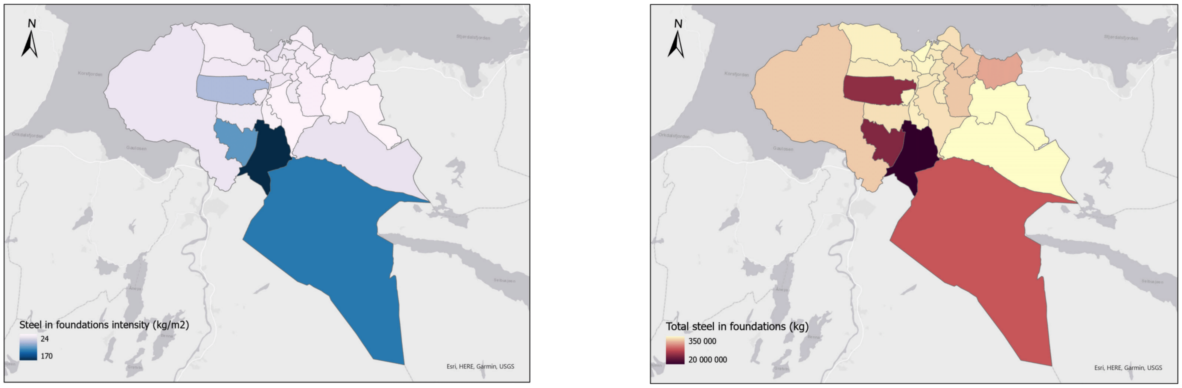


Figure 25: Soil types in Trondheim. Data from NGU (2023)

Keeping this in mind when analysing the results of the model as seen in Figure 26, it becomes clear that most steel is found in foundations in areas which are placed on peat and bog, such as Klæbu, Tiller and Byåsen. Additionally, as the results for foundation intensity do not deviate from those calculated by Ilgemann (2023) despite the Material Insities being changed, it shows that the changing of loads did has less of an effect on foundation volume than soil type does. This reiterates Ilgemann (2023) recommendation about not building on peat and bog. Furthermore, Byåsen stands out in terms of total stock of foundations. This could be related to the rapid expansion of the building stock in this area in the last decades, with a high ratio of SFHs with few floors, which will give a high foundation/floor area ratio.



(a) kg steel per m^2 of floor area per neighborhood.

(b) kg steel in total per neighborhood.

Figure 26: Results of foundation model

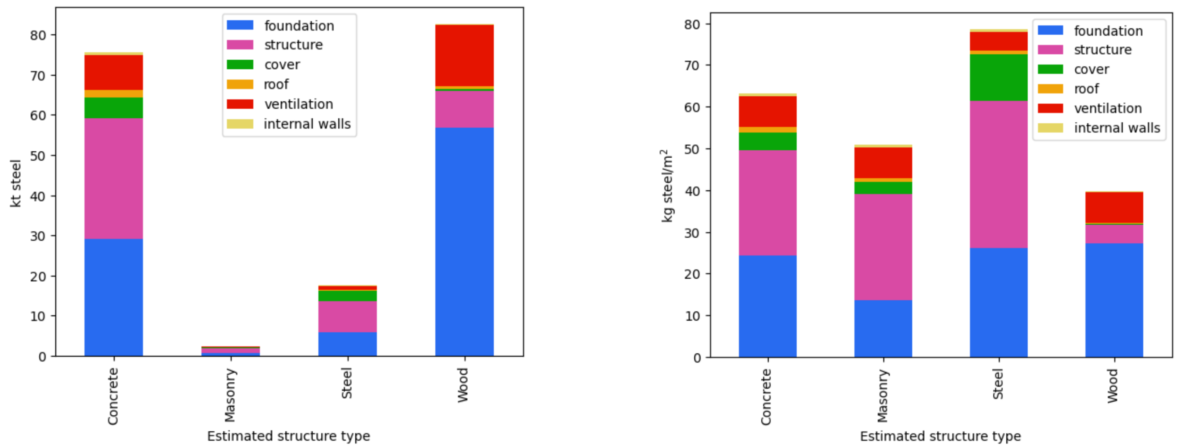
3.3 Building components

Here, the results of the model with the material intensities applied are given.

Table 8: Total steel found in stock, by component

Component	Steel stock (kt)	Share of total
Foundation	92.36	52%
Structure	48.31	27%
Cover	8.34	5%
Roof	2.63	1%
Ventilation	25.46	14%
Internal walls	0.92	1%
Sum	178.02	100%

Table 8 show the total stock of steel in each component in the Trondheim region. The foundations contribute the most, while the structure is second. In total, it was calculated that there is 178 kilotonnes steel embedded in the Trondheim residential building stock of the cohorts 1990-2022.



(a) Total stock

(b) Stock per m^2

Figure 27: Components per structure type

As can be seen in Figure 27, for each of the structure types, the different components have a different impact on the total, based on the MIs. For steel buildings, the structural system is the most important component, while for wooden buildings, it is the foundation which has the most impact.

For the steel per m^2, it is unsurprisingly the steel building that has the most steel per m^2 in all categories, except Ventilation, which is the same for all. There, the cover has a much higher influence here than in all of the other types. This is due to the type of cover that is used here, composite flooring, which requires a lot of reinforcement, while for other types, other materials are used.

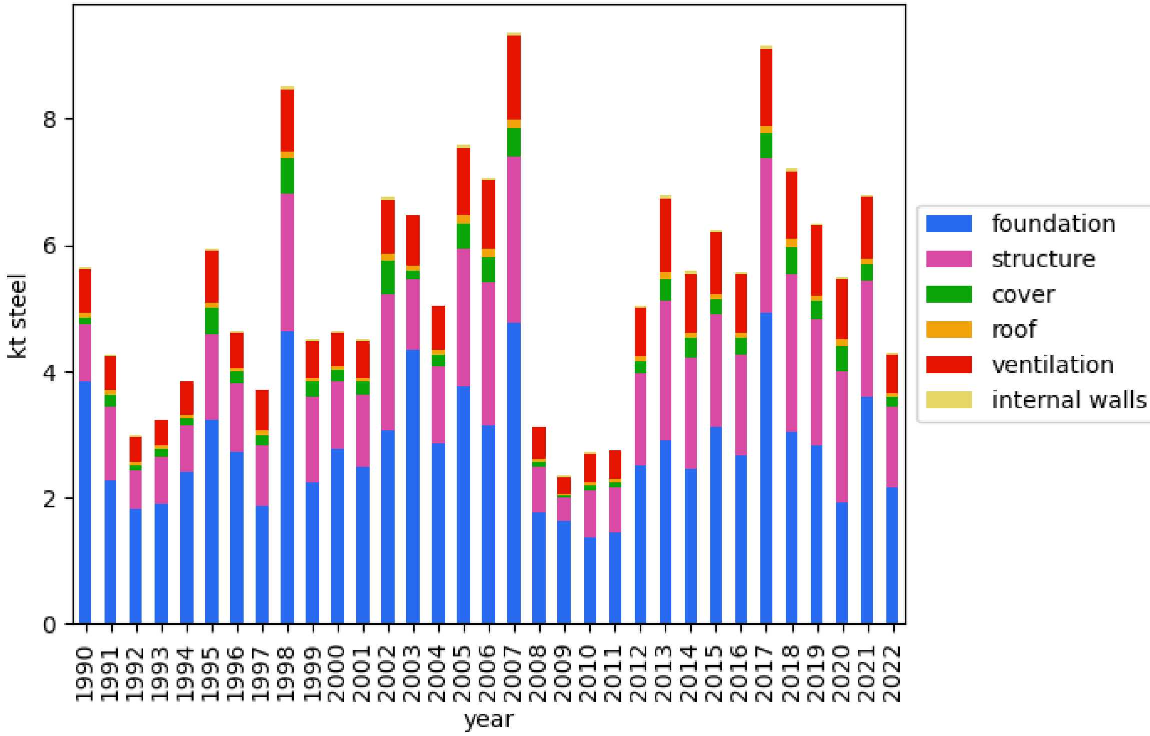


Figure 28: Components of each cohort

In Figure 28, the composition of the different cohorts can be seen. The composition remains relatively steady over time. This is reasonable, as the Material Intensities are reliant on the different structural types and use types, where the share has been quite steady over time (see Figure 21b).

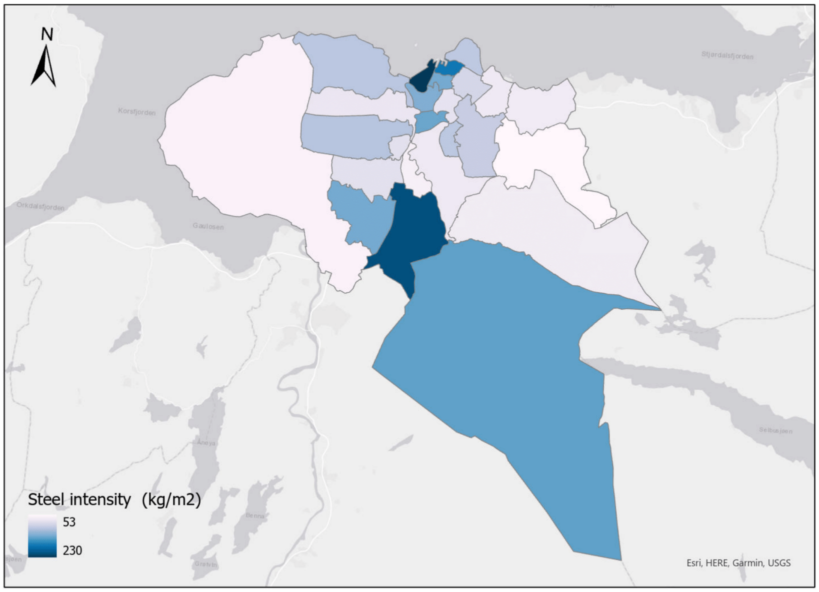


Figure 29: Steel intensity per neighborhood

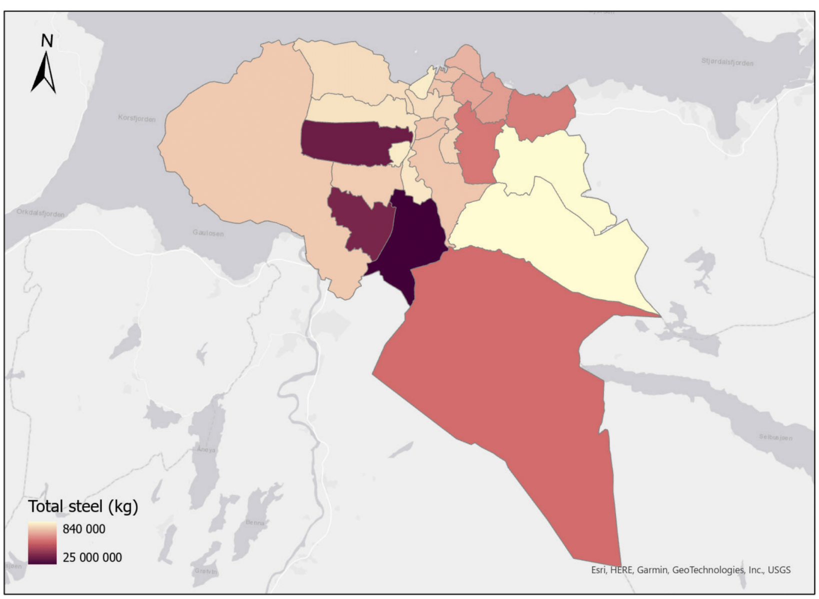
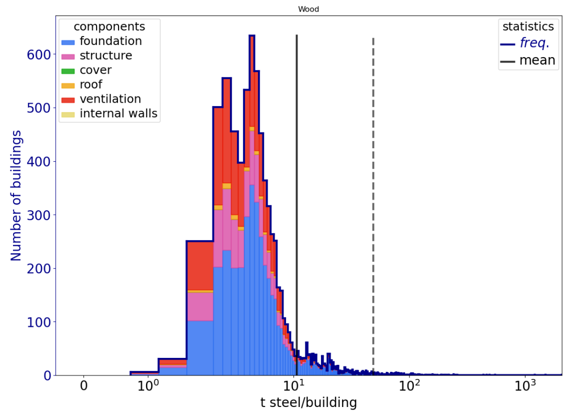
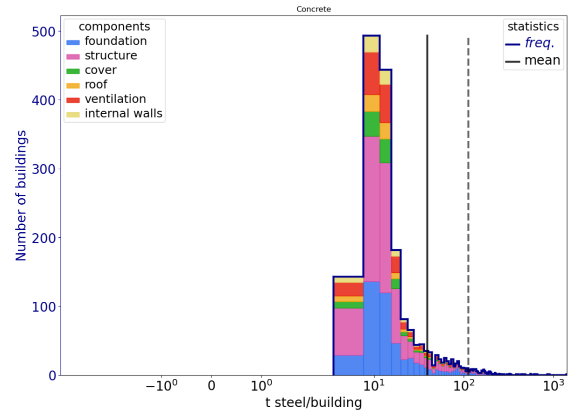


Figure 30: Total steel per neighborhood

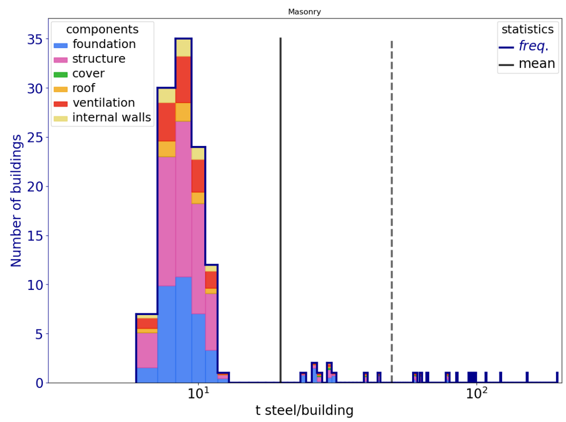
In Figure 29 and 30, the steel intensity and steel per total are illustrated. Here, the same trend as for foundations continue. This is reasonable, as the foundation accounts for most of the steel. However, one area that stands out in the Midtbyen, which has the highest steel intensity (Figure 29). This deviates from the results of the foundation, so the remaining components must be the difference. There are more tall building in Midtbyen, which are more likely to be steel or concrete buildings. Furthermore, this tendency could be strengthened by the fact that there are many buildings in Midtbyen that are not only residential, but can be split between residential and non-residenial, like a store on the first floor and apartments above. However, this will be coded as a residential building in the Cadastre, leading to heavy buildings. Additionally, while there is a relatively high amount of steel in Midtbyen, the total floor area is relatively small compared to the rest of the neighborhoods. With a high steel content and low floor area, the intensity becomes high. We can conclude that most of the steel is found in Tiller, Heimdal and Byåsen, while Midtbyen is a neighborhood with a high potential for gathering structural steel.



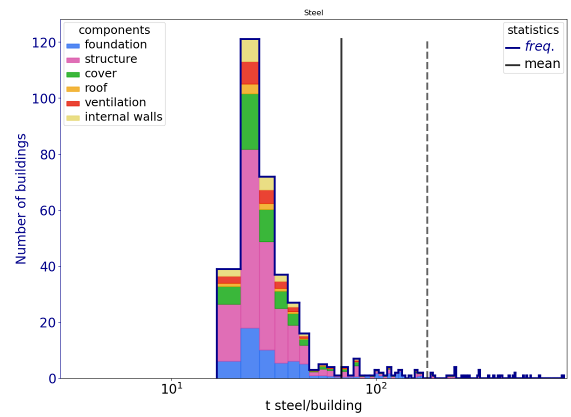
(a) Wooden building



(b) Concrete building



(c) Masonry building



(d) Steel building

Figure 31: Histograms of the stock of steel of different structural types, on a logarithmic scale

The maps study the steel average for each neighborhood. However, it it is also useful to consider what the distribution looks like.

Here, the distribution is plotted on a logarithmic scale, and the components are stacked to show the total steel content of each building. For all the types, the mean is higher than the median. This is a result of the statistical model and is connected to the few big buildings that exist, which naturally have a significant amount of steel per building.

For the wooden buildings, there are two peaks. This suggests that there are two types of buildings that were grouped together. Indeed, there is great variation in wooden buildings, and it is also the most common structural type of building. The MIs for the different use type also differs depending on the use type - for AB of wood, the MIs account for some structural components of steel and hollow concrete slabs being used for structural integrity, as tall wooden buildings are rarely built using only wood components.

Lastly, for wooden buildings, ventilation constitutes a larger part of the steel stock than for the other types. This is a reflection of the low steel content in other components. However, the ventilation MI is the same for all types, and has a high uncertainty, so this should be studied more.

3.4 Embodied carbon emission

The embodied emissions are calculated based on the Emission Intensities described in the methods section. Results can be seen in Figure 32.

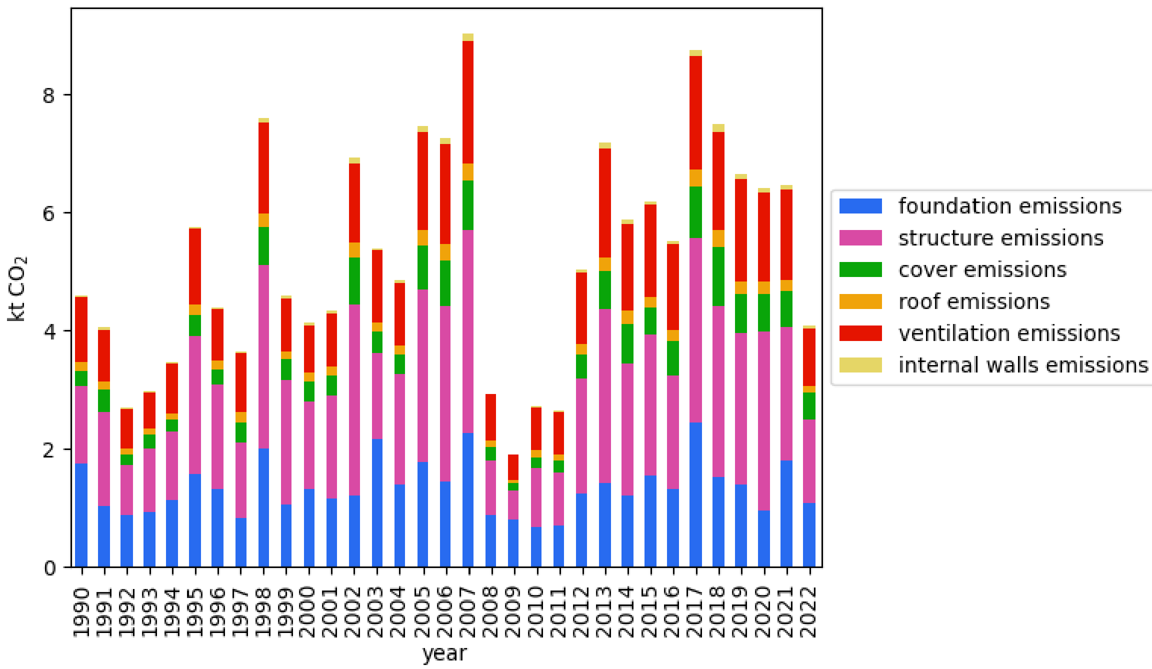


Figure 32: Emissions per cohort

Table 9: Embodied emissions in the stock

Component	Embodied emissions (kt CO_2))	Share of total
Foundation	44.16	25.5%
Structure	65.8	38.0%
Cover	15.41	8.9%
Roof	5.76	3.3%
Ventilation	40.13	23.2%
Internal walls	1.87	1.1%
Sum	173.13	100%

This represents 173 kilotonnes of CO_2. There is quite a big difference in the emission intensity of types of steel, depending on its purpose and strength. It should be noted that this part of the model is sensitive to the emission intensity used in the calculations. This is reflected in the difference in ratio of the total for the different components in the two layers of the model. The contribution of the foundation to the total steel was 52 %, but for emissions, it is 25 %. This is due to the low emission intensity, while the structural components, which contributed 27 % of the steel stock, account for 38 % of the total emissions. This emphasises the importance of emission-efficient production in addition to material efficiency.

4 Discussion

This section will include a discussion about the results and its consequences. Furthermore, an application of the results in the form of a qualitative discussion about the potential for the reduction of embodied emissions will be made. This is based on the literature study, interpretations of the results, and discussions with industry professionals.

4.1 Reduction of material use

Arceo et al. (2021) point out that although there has been a significant focus in the field on quantifying materials for reuse, construction is happening at a higher rate than demolition projects. Therefore, it is necessary to consider pathways to use less materials for the same services. One of the goals of this thesis was to quantify the steel in the stock and find out where it exists. This was done both in terms of cohorts in a geographical aspect and for different components in the buildings themselves. The results can inform where there is most potential for reduction of steel used.

In terms of components, the foundation and structure were found to be the most significant. Considering the different building types and the different MIs found for low and high buildings, the number of stories does not seem to affect the material intensity much, even for the structural components. However, more real-life data is needed to make more certain conclusions on this. Nevertheless, it is clear that foundations are the biggest steel sink for all building types. A way to decrease steel use would be to get more service out of the same foundation - the way to do this would be to build more upwards rather than sideways. However, the term 'CO_2 premium' is often used for increasing building height, as it is expected to require more structural materials to account for lateral loads. However, Ytrehus (2015) investigated this phenomenon and found it negligible until 12 stories, making it a good alternative for a city such as Trondheim, where high-rise buildings are not very common. Furthermore, as Ilgemann (2023) pointed out, one of the critical policies the municipality could implement is to avoid building on peat and bog, as this induces large foundations. This also applies to reinforcing steel.

One can take several approaches when aiming to use less material, both technological and behavioural changes.

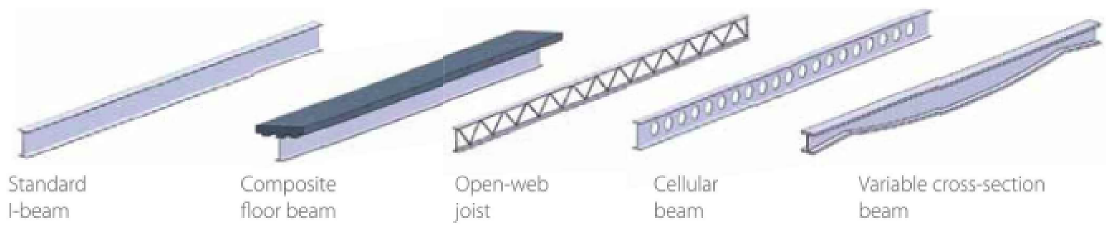


Figure 34: Illustration of different types of beams. From Allwood and Cullen (2012)

In their book 'Sustainable Materials: With Both Eyes Open' Allwood and Cullen (2012) discuss different ways of reducing material use, with a specific focus on steel. Here, options for material-efficient designs are presented. Construction engineers have a large role to play when it comes to reducing input materials, and design choices have a big impact. Allwood and Cullen (2012) discuss how standard universal beams, which are key components of steel-framed buildings, can be optimised by changing the design to accommodate holding the load only where it is necessary and make the beams slimmer in the rest of it. In practice, the standard universal I-beam is often used, with a constant cross-section. This design is chosen due to the ease of manufacturing. However, Allwood and Cullen (2012) found that other designs (seen in Figure 34 had the potential of saving up to 80 % of the weight. This applies to the structural steel components and beams found in steel buildings (27 % of the stock), but less to other components, so it is limited in scale.

They also discuss how the rebar that is used for i.e foundations can be reduced. Here, it is often an issue of specifications, where the geometry is made as simple as possible, as it is easier and quicker. Of course, this design needs to withstand the highest load applied to the component, even though it is not necessary for the whole foundation. This is an example of the phenomenon of rationalisation [3], which is a general problem for steel structures, so the final design often does not end up using the least amount of material D'Amico and Pomponi (2018) and Helal et al. (2020). This sentiment was also agreed upon by structural engineers (H. Dahle, personal communication, 15.02.23), who described that when hired to make designs, there would not be enough time allocated to design reinforcement for ie. all beams individually, so one ends up repeating designs. Of course, one must take loads into account due to the safety of the structure, so the reinforcement can end up being excessive.

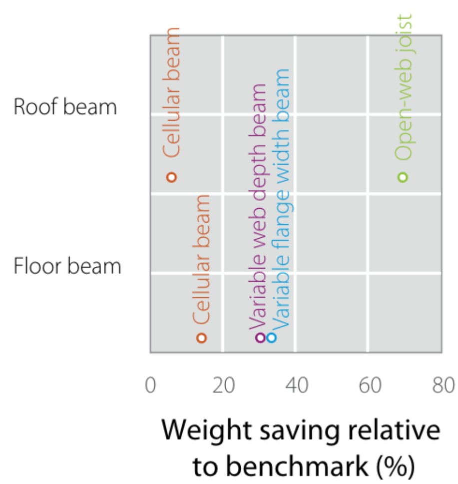


Figure 33: Saving potentials of different types of beams. Reprinted from Allwood and Cullen (2012)

[3]"structural engineers [minimizing] the overall number of different member sizes and sections, usually arranging the columns layout on a regular orthogonal grid pattern to achieve maximum component repetition." (D'Amico and Pomponi, 2018, p. 237)

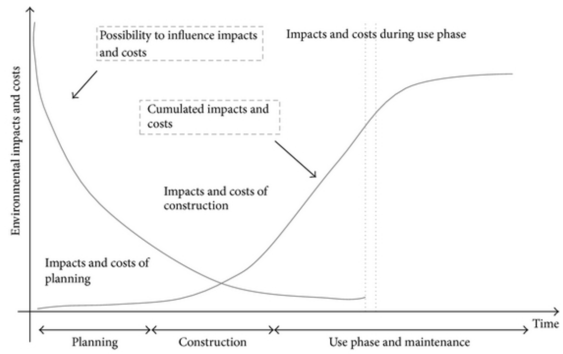


Figure 35: Early planning for sustainability in the design process. Reprinted from Bragança et al. (2014), based on Kohler and Moffatt (2003)

These problems were the aims of D'Amico and Pomponi
(2018), who developed a computational tool to optimise the use of steel in the structures of a building, in order to lower both labour and material costs. This could be an important tool for smarter engineering in the future.

Material efficiency should be considered when designing a building. It is generally an agreed-upon fact in the sustainable building community that early intervention has bigger impact for a lower economic price, as seen in Figure 35. This idea was put forward by Kohler and Moffatt (2003) in 2003, when LCAs of buildings were much rarer than they are now. While the emissions of the other materials in the buildings have not been studied in this thesis, it is a general consensus that material and design choices should be done on a case-by-case basis to find the design with the lowest environmental impact.

For example, as Hart et al. (2021) found that for apartment buildings, wooden buildings had less embodied carbon per unit area than reinforced concrete, with steel being the most CO_2 intensive (illustrated in 36). However, this is a significant overlap, suggesting there is potential for low-emission buildings for all types, and there is no easy answer for choosing the 'best material'. Furthermore, the introduction of TEK17, which from the 1st of July 2032 requires CO_2 emission budgets to be made for all apartment and non-residential buildings, should help give the data foundations necessary for better decision making (Direktoratet for byggkvalitet, 2022a).

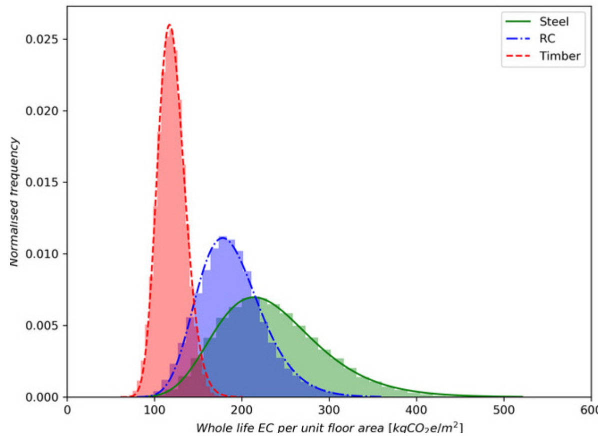


Figure 36: CO_2 of embodied emissions of structures per unit floor area. Reprinted from Hart et al. (2021)

The technological development in the industry leads to new opportunities, as studied by both Thøgersen (2019) and Nilsen (2019), who discuss how the integration of BIM integration in new buildings and the consequential LCAs can reduce emissions by giving early insight to the sources of the biggest emissions.

However, due to the scale of the climate change crisis, technological change is not enough. Behavioural changes include decreasing the UFA required per person, and increasing the life size of buildings. In recent decades, the UFA per person has increased (Thyholt et al., 2009), indicating that there has been a behaviour change in the way we build and live. However, if the function of the building is to provide shelter, it should be possible to decrease this number, although this would require significant societal change.

Furthermore, a very effective tool for reducing embodied emissions would be to increase the lifetime of buildings to reduce the need for new construction. Here, both the functional and technical lifetime should be considered. This means using materials that can withstand the test of time but also be flexible for changes in the user's preferences without having to demolish the building. However, there is a dilemma here. A common way of preparing the buildings for a longer lifetime is to design the building with a stronger structure than necessary as a way of increasing the lifetime to accommodate for possible use change later or allowing for more storeys to be built on top of the existing building (Z. Miklós, personal communication, 8.05.23). However, this often uses more materials to account for higher loads and costs more upfront.

4.2 Reuse & recycling

The model also quantifies the steel represented by cohorts. This is useful information when planning to recycle and reuse steel in buildings that will be demolished. In a circular economy, the demand for steel for construction would not be higher than the current outflow. Considering the component level of the steel stock, this allows for better planning. For example, reinforcing steel in concrete is not suitable for reuse, but must be recycled due to the specific shape it needs to welded in and the fact that it is imbedded in the metal. However, if disassembly is done properly, there is a high potential for reuse of steel columns and beams. From the results, we can see that around 48 kt of structural steel becomes available in the building stock.

When discussing materials in the circular economy, steel is an interesting case. This is because it is one of the few materials that are already almost fully recycled in our linear economy society (around 90% of all steel at the end of its first lifetime is recycled (EURIC, n.d.)). This can first and foremost be attributed to its high economic value and easy recyclability, as it is magnetic and therefore easy to separate in the waste plant. It became clear in the analysis that the embodied emissions are lower for steel types that contain a higher scrap-steel ratio. However, as the steel scrap will already be used in some way, due to the already high recycling rate, simply encouraging high rates of recycled content in a specific project is not enough to reduce emissions overall.

When a building is demolished, the materials are, to a high degree, separated on-site due to incentives which reward a high recycling rate and better-sorted waste. Usually, concrete is crushed, and the mix of concrete and reinforcing steel is brought to the recycling facility (A. Staberg, personal communication, 25.01.23). Here, it is taken out by magnets. Then it can be prepared for smelting and recycling. However, this process leads to some emissions from the transportation of the materials and the processing energy. Therefore, recycled steel is associated with 50-75 % less energy use than primary production is (Drewniok et al., 2017). Furthermore, steel can be infinitely recycled in ideal conditions and keep the same properties. However, due to impurities, the quality can downgrade throughout the recycling cycles (Daigo et al., 2020).

To avoid this energy-intensive process, one should instead look to the direct reuse of components, which is higher in the waste hierarchy. The component could be used either for its intended purpose or for something new. This is uncommon in the building industry, but interest in it has increased in recent years. Reuse can be in the same building by simply reusing the structure when a new building is built. It could also be done by dismantling individual pieces and reusing them in different projects (Fuglseth et al., 2020).

Fuglseth et al. (2020) gives an overview of the state of building material reuse in Norway today, considering the potential for emission reduction and discussing barriers. It was found that reusing steel components would reduce emissions by 80 % compared to using recycled materials (Widenoja et al., 2018). And in a case study where structural steel beams were reused, when compared to using virgin materials, the emission saving was 97 % (Fuglseth et al., 2020). In other words, there is evidence for implementing reuse practices in the construction industry.

The results point to some places one should focus on reuse efforts. Structural components are significant in terms of emissions but have high requirements for documentation and testing due to the importance of safety. One can also look to non-structural materials which have lower documentation requirements and therefore are easier reused. Examples of this is roof cladding steel plates, which can be plucked off and reused. Additionally, ventilation systems are getting more attention with regard to reuse. Straight pipes of standard sizes can quite easily be used in another system (Kron et al., 2022).

However, there are many barriers against this. This includes economic barriers: dismantling the parts for reuse takes more time than traditional demolition, so labour costs more than the saving on new material (Mathisen, 2023). Furthermore, there are technical barriers: such as the welding in place of components, which makes for a more challenging dismantling, and the fact that for safety, all components must fulfil today's building codes and requirements (Fuglseth et al., 2020). As there is often a lack of documentation for the buildings, this makes it necessary to do tests on the components, which can be time-consuming and expensive. Another barrier is that the reuse of components disrupts the usual workflow of a building project (Fuglseth et al., 2020). If there is no immediate use for components, there is a need for space for storing the components, as well as transport. However, with an expanding market where several platforms for reused building components are being developed (Kommunal-og distriktsdepartementet, 2022), this problem could decrease. Furthermore, as of this year, for demolition projects of non-residential buildings and ABs, it is compulsory to do a report on components which can be reused ('Ombrukskartlegging') before demolition (Direktoratet for byggkvalitet, 2022b). This will give a better overview of available materials, which can then be planned for future projects. For buildings that will be demolished in the future Akanbi et al. (2018) has investigated the role BIM can have in salvaging materials. However, as it is urgent to reduce emissions now, building stock models like the one described in this thesis can be useful to bridge this gap. Here, it was found that 178 kt of steel exists in the Trondheim building stock 1990-2022. However, reinforcement in concrete is not suitable for direct reuse, so the focus should be on steel structure buildings in this case. Additionally, concrete components like beams and hollow concrete slabs can also be reused whole if they are dismantled and installed in the right way. This also should motivate designing buildings with easy dismantling in mind, by bolting instead of welding and making sure documentation on properties is available (Fuglseth et al., 2020).

4.3 Reducing the emission intensity

In this thesis, there has been a significant focus on material efficiency as a way to reduce emissions. However, there is also some technological development in the field, which can be used to reduce the emissions related to steel, even without reducing the final steel demand. First is a new steel-making process, which uses hydrogen as fuel, rather than coke, popularly called 'green steel'. If renewable energy is used for the process energy, this dramatically reduces emissions from the production process, with about 95 % "H2 Green Steel" (2023). There is already a production plant in Sweden with plans to start production by 2025 ("H2 Green Steel", 2023). However, if the world is to shift to steel made from this source, there needs to be a significant upscaling of hydrogren production.

Next, carbon capture and storage (CCS) is also in the works for the industry, and the IEA has estimated that by 2060, 21 % of the world's steel production needs to be done with CCS IEA (2020). However, due to the high costs, no production has been put into place yet.

Optimisation has been mentioned previously with regard to reducing materials. However, it is not always the case that lower material use leads to less emissions. In the case of ventilation systems, for example, the size of the pipes influences the energy necessary to pump the air (in general, the smaller the pipe, the more energy is used) (J. Tønnesen, personal communication, 14.04.23). The challenge is finding the right balance, so operational emissions do not improve on account of embodied emissions. As it is possible to calculate energy use through simulations and with information about emission intensity for the materials, optimisation models can be used for dilemmas like these (J. Tønnesen, personal communication, 14.04.23).

Overall, while there are some opportunities for emission reduction, material reduction should have priority.

4.4 Limitations & Uncertainties

4.4.1 The functional unit

For the results, the chosen unit is kg/m^2. While this is the most common unit used in building stock models, this is something which should be reflected upon when the ultimate goal is to provide as much service per unit material as possible. Arceo et al. (2021) quantified the material intensity for several different units: per m^2 floor area, per building and per bedroom (used as a proxy for the number of people in the household). Here, it was found that material intensity had a more significant variation in the 40 buildings they studied when the materials were normalised on building counts and bedrooms, leading to higher uncertainty. This supports the use of m^2 as a normalising unit. However, in a more recent study, they considered the effect different functional units have when considering MIs of building archetypes in Australia, Canada and Indonesia Arceo et al. (2023). Here, it was found that the Indonesian buildings had the highest MI per unit floor area due to their construction techniques and high use of concrete rather than wood, which was the Canadian archetype. However, this difference dramatically shifted when the MI was normalised for the number of bedrooms, as there were fewer and bigger bedrooms for the same area in Canada and Australia compared to Indonesia. This showed the difference the functional unit could make in understanding the results. As a building is meant to perform a specific function - being a shelter - this could serve as a better unit if the goal is to reduce materials.

This model only considers one city, where the building style and socio-economic factors which lead to the differences in Arceo et al. (2023) are not as relevant, so it is still relevant to consider the steel per m^2. Furthermore, there is no data available for the buildings in the Cadaster on how many people reside in the building or how many bedrooms there are. Therefore it was not possible to include this as an FU. However, this makes an important point if the results were to be compared with different regions. Additionally, it brings up an important point about the importance of lowering floor area, relevant to policy about the final demand for materials, which should be considered for maximising service while keeping consumption low.

4.4.2 Environmental impact

In the field of Industrial Ecology, there are many well-developed methods of quantifying many different types of environmental impacts, such as LCA, LCIA and IOA. In this study, the environmental impact is only considered as climate change impact at the endpoint level. This is both because this is one of the main impacts of steel production, but also due to the scope of the study and data availability.

Furthermore, there is only one material considered in this study. Therefore, there is no basis for making conclusions on which types of buildings have the lowest embodied emissions overall, as, obviously, a building is built from many other materials than just steel. Although steel has a high relative CO_2 emission per kg, it often has the favour that there is less mass required to construct a building than, for example, a concrete building. Therefore, to understand the building stock on a bigger or individual picture, the scope would need to be extended to more materials, and an LCA would need to be performed.

4.4.3 Modelling choices

Ortlepp et al. (2018) discuss how uncertainties are dealt with in different building stock models. They state that in bottom-up models, uncertainties are often dealt with simply, as the base data rarely fulfils "the quantitative requirements of statistical approaches to the estimation of uncertainty" (Ortlepp et al., 2018, p. 165), which limits the use of i.e. sensitivity analysis. Therefore, most deal with uncertainties by either determining some confidence ratings or uncertainty intervals, or by qualitative assessments of the data sources and their reliability and how representative it is in terms of time and geography (Ortlepp et al., 2018). However, several studies have attempted to compare their results with others, although this presents problems due to different system boundaries.

In this model, where assumptions are made in multiple steps and different data sources are combined, quantifying uncertainties is a difficult task. A qualitative discussion is seen as more appropriate, in line with the common method in the literature. Therefore the limitations will be discussed with a view to how they could influence the results.

First, there is no standard terminology or classification for the use types of residential buildings. For example, Sandberg, Sartori, Vestrum, et al. (2016) use the types Single Family House, Terraced House, and Multifamily house, and there is no further explanation of exactly which types these encompass. The Cadastre data contains 25 detailed building types (on the second classification level) under the code 'Residential' ('Bolig'). The classification of the cadastre building codes was done by me, based on my understanding and definition of the building types. As this classification was done consistently for the sample and the cadastre data, this does not affect the results of the structural type determination much. However, the MI data can become less reliable as a result of this, if the conditions of the types defined in this model, and the source of the MI data are different. This uncertainty is a consequence of using secondary data in the model. However, this only affects some of the types, while some building codes are quite straightforward to identify, such as SFHs.

Next, classifying buildings into different structural types is a modelling choice that does not necessarily reflect reality. In reality, many buildings are composite and can contain both reinforced concrete and some wooden structures. To make the collection of MIs a realistic endeavour, it was seen as necessary to make some groupings. As mentioned earlier, the certainty of the classification was strengthened by a professional, but as this sample is used to classify all buildings, it inherently introduces uncertainties. Additionally, it is quite a small sample, with few factors informing the type (size of the footprint, how many floors, and use type). So, it is expected that there will be some buildings for which the prediction is incorrect. This becomes clear when studying the individual buildings in the histograms. But, as the model covers many buildings, it is assumed that the values will converge to the mean, giving a representative output. Another factor that could have been included in the machine-learning model is the location of the samples. This was not included, due to time constraints and lack of samples in each region, but as this gives another input to the model, this could have improved the accuracy of the results.

The biggest uncertainty comes from the Material Intensities. As Ortlepp et al. (2018) describes, there are for many models scant data sources, and collecting MIs are associated with a lot of effort and time. In this work, there were several barriers to collecting these, related to time constraints and lack of responses. Several assumptions had to be made in this model due to lack of real-life data. This includes assumptions on floor thickness, amounts of internal walls and to some degree, the materials used. This was necessary to get a working model, but it creates significant uncertainties.

Another point is that renovation should also be considered as embodied emissions. However, this is not included in the model. There are several reasons for this. First, there is quite little data on renovation cycles in Norway, except for general estimations of cycles regarding energy upgrades. However, for steel, this is less relevant, as the structural elements and foundation of the building tend not to be replaced.

In the embodied emissions, only phase A1-3 (production stages) is included, not A4 (transport). This is due to a lack of data about transportation distances. In Ilgemann's model, the transport of concrete was studied. Here, it was found to be 1% of total emissions. However, there are several concrete mixers in the Trondheim region. There are also companies providing steel in Trondheim, but it is not produced here, and steel comes from the global market. As opposed to concrete, which can be mixed with water in Trondheim, steel is already heavy in the transportation phase. However, as there is no data on transport distances and suppliers in Norway, which would add another layer to the model, this was excluded.

4.4.4 Validation: Comparison with other studies

Table 10: MIs found in literature (kg/m^2

Study	**Location**	**SFH**	**TH/MFH**	**AB**
Lanau & Liu (2020)	Odense, Denmark	10.6	9.0	11.6
Ortlepp et al. (2018)	Germany	-	126	-
Kleemann et al. (2017)	Vienna, Austria	-	43 (metals)	-
Gontia et al. (2018)	Sweden	40	63 (wooden buildings)	-
This study	Trondheim, Norway	48.2	48.3	69.0

In Table 10, data points about steel from the literature are compared to the results of this study, normalised for floor space over the common use types used in the literature. As seen, there is a large variation within the literature. This is natural, due to different system boundaries and locations studied. Nevertheless, the values of this study are in the same scale of magnitude as the comparative studies. Furthermore, they lie in the middle between the highest and lowest values for MFH buildings. It could also be thought that the values are higher than average, as the MIs are more detailed and account for more of the steel in the buildings. Furthermore, many models operate with only one or a few archetypes of buildings. When the model is based on different structural types, rather than considering a whole cohort to be Wooden, this will result in different results.

The comparison confirms that the final result of the quantities in the stock depends on the resolution of MIs. Furthermore, MIs differ between different locations and are not transferrable, so more research and data gathering should be done to establish MIs with higher uncertainties.

4.5 Future research

The building stock analysis field of study requires better data and higher resolution of the results. Many studies today generalise MIs based on only a few aspects, such as cohort or use type. However, this makes for large variation in the results. Future studies should consider more real data and have a higher resolution in terms of types. New technology, such as BIM models and Artificial Intelligence, could aid this. AI in the form of Machine learning has already been used in some models, such as Ghione et al. (2022), where a model for recognising structural type was developed. Here, training data was manually coded from Google Street View, and then the model was taught to identify structures based on the pictures itself. However, this model was moderately successful and failed to recognise more complicated structures, such as reinforced concrete. Therefore the technology needs to be advanced. Furthermore, with the digitalisation of the building industry happening today, many more sources of information are available through BIM models. However, it is crucial that this data becomes available to researchers and policymakers.

Furthermore, as the discussion MIs revealed, more specific MIs should be calculated. This could be based on case studies or more accurate archetypes. Here, there is a possibility for better data sources, through the building application process. Having this information available has made the calculation of MIs in Finland more consistent and accurate (Nasiri et al., 2023). Therefore, the municipality should ask for more details in the building application process.

Next, as discussed, there is much more research on residential buildings than non-residential buildings (Aldebei & Dombi, 2021). However, the findings of Ortlepp et al. (2016) revealed that on average, there is more steel in non-residential buildings than in residential. Furthermore, they often have shorter lifetimes, making component reuse more relevant. Therefore, more emphasis should be put on non-residential buildings and the potential for urban mining here.

Lastly, this model only covered cohorts going back to 1990. Due to the long lifetime of buildings, studying older cohorts could be more beneficial for planning purposes, as these buildings will most likely be demolished first. This would require acquiring new MIs, based on different construction techniques and a new sample of buildings, but otherwise, the same method could be applied.

5 Conclusion

In this thesis, the steel stock in residential buildings in Trondheim constructed between 1990 and 2022 has been modelled and analysed, with the motivation of having a better base for planning for reuse and recycling, as well as reducing demand for steel made from virgin materials. The model presents a novel approach to bottom-up building stock modelling by allowing for the use of more specific Material Intensity coefficients, using machine learning to determine the structural types of the buildings. This increases the resolution of results and allows for analysing the stock on several levels, such as by components and structural type.

It was found that there are 178 kilotons of steel in the residential building stock within the system boundary, which has led to 173 kilotonnes CO_2 of embodied emissions. Furthermore, it was found that some areas in Trondheim have a higher steel intensity than others. This includes Klæbu and Tiller, which are placed on peat and bog soil, requiring a heavy foundation and a substantial amount of reinforcement steel to stabilise in the soil. Furthermore, it was found that the foundations is the component that contributes most to the total steel stock. An efficient way to reduce this impact is to use less reinforcing steel in foundations for the same service. This can be done by smarter design or by building taller buildings.

Furthermore, it was found that the highest potential for reusing components lies in structural elements in steel buildings. As it was found that apartment buildings have the highest probability of being steel buildings, this is where efforts for reuse should be made. Furthermore, due to today's economic and legal barriers to reusing structural steel, there should also be a focus on components which require lower effort to reduce, such as ventilation pipes or roof plates, as they still contribute to the total emissions.

Lastly, there should generally be a focus on embodied emissions in the construction of new buildings, as these are irreversible and occur in the present time, as opposed to operational emissions, which could be reduced with new technology.

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Appendix

5.1 Sources of Material Intensity coefficients

Component	Type	Assumptions	Source
Foundation	Slab		Average of two data sources: 1) Estimation from building engineer. 2) Steven (2021)
	Strip footing		Salam and El-kady (2017)
	Spread footing		Camp and Assadollahi (2015)
	Deep pile footing		Skanska (2020)
	Basement		Estimation from building engineer (H. Dahle, personal communication)
Structure	Steel		Average of two data sources: 1) Hart et al. (2021) 2) Meters of beams + columns and secondary columns from OneClick, weight per meter: Stene Stål (2023)
	Concrete		Average of two data sources: 1) Hart et al. (2021) reinforcement in concrete 2) Meters of concrete beams + columns from OneClick, assumed 135 kg/m3, based on information from building engineer
	Wood		Hart et al. (2021) connecting steel parts
	Masonry		No data, treated the same as concrete
Ventilation	All		Based on estimation of steel in an office building from H. Bergsdal (personal communication). Reduced number with 50 %, based on requirements for airflow in residential vs. non-residential buildings
Cover	Concrete	Hollow concrete slabs	Steel content in EPD, recalculated weight per tonne to per m2 based on information in EPD:
	Wood	Wooden cover, except for Abs	Wooden building - Sintef Teknisk godkjenning: https://www.sintefcertification.no/Contents/Index/174
	Steel	Reinforced concrete slab	Average of two data sources: 1) Hart et al. 2) Assumed 0.15 m concrete slab (based on OneClick) and 130 kg/m3 concrete, based on information from building engineer (H. Dahle. personal communication)
	Masonry	Wooden cover, except for ABs	Assumed same as wood
Ceiling	Concrete	Hollow concrete slabs	Same as for cover
	Wood	Assume length of 10 m (median) and 60 cm in between	Based on steel content in EPD: Norske Takstolprodusenters Forening (NTF) (2016)
	Steel	Steel roof covering	Weight per m2: Sariola and Hedman (n.d.)
	Masonry		Same as for cover

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