Bachelor's thesis at the Lucerne School of Engineering and Architecture

Title	**Embodied and Operational Environmental Impact of a Building – A Case Study**
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Abstract German

Im Rahmen einer Fallstudie wurde in dieser Arbeit die Nachhaltigkeit eines Mehrfamilienhauses (MFH) bewertet. Ziel der Studie war es, die Gesamtumweltbelastung des MFH Lisa zu ermitteln und den prozentualen Beitrag des verkörperten und des betrieblichen Teils zu untersuchen. Für dies, wurde eine Lebenszyklusanalyse angewendet. Für die Berechnungen wurden hauptsächlich die Normen des Schweizerischen Ingenieur- und Architektenvereins (SIA) verwendet. Die Ergebnisse zeigen, dass die Gebäudemasse mit den enthaltenen Materialien und Geräten einen Anteil von rund 73 Prozent an der gesamten Umweltbelastung hat. Das Material mit den höchsten Umweltauswirkungen ist Stahlbeton. Die Arbeit zeigte, dass bisher vorallem Anstrengungen unternommen wurden, um zu einem effizienteren Betrieb zu gelangen. Dennoch sind vielversprechende Konzepte und weitere Forschungen im Gange, so dass bald auch die Baumasse nachhaltiger gestaltet werden kann.

Abstract English

Within the framework of a case study, this thesis evaluated the sustainability of a multi-family house (MFH). The aim of the study was to find the total environmental impact of the MFH Lisa and to investigate the contribution percentage of the embodied and the operational part. For this, a Life Cycle Assessment was applied. For the calculations, the standards of the Swiss Society of Engineers and Architects (SIA) were mainly used. The results show that the building mass with the included materials and appliances has a share of around 73 percent of the total environmental impact. The material with the highest environmental impact was found to be reinforced concrete. The work showed that most efforts were previously made to arrive at a more efficient operation. Nevertheless, promising concepts and further research is underway so that soon the building mass can also be constructed more sustainably.

Place, date Steinhausen, 10.06.2022

Executive summary

The building sector is a major consumer of energy and materials. To save resources and reduce the environmental impact, new approaches to material selection, use and recycling must be found. In order to evaluate existing buildings or to set the right course for sustainable construction, an environmental analysis is needed. Nowadays, this is increasingly done based on Life Cycle Assessments (LCA).

In this paper, a multi-family house in Uster, Zurich, Switzerland was used to investigate its environmental impact over a lifetime of 60 years. Using the framework for LCA according to the International Organization for Standardization (ISO) 14040 and ISO 14044, specific building materials and equipment were analyzed regarding their embodied environmental impact. For this purpose, the entire building was measured in detail using the Bluebeam Revu 20 building simulation software. The recorded building fabric could then be assessed according to its environmental impact in terms of greenhouse gas (GHG) emissions and environmental impact points (EIP). For this purpose, the database of the Coordination Conference of Building and Real Estate Bodies of Public Builders (KBOB) was used. In addition to that, the use stage was analyzed in terms of heat and electricity consumption. For this reason, the heating demand was calculated with the calculation tool according to SIA 380/1:2016 and standard values were assumed for the electricity and hot water demand.

The main objective of the work was to determine the total environmental impact of the existing building and the total environmental impact during its operation. In addition, it was to be shown how strongly the two areas contribute to the overall result. Subsequently, possible improvements for the building sector were to be proposed based on the existing literature and the findings.

The work showed that a multi-family house built according to today's standards is very efficient in use and low in resource demand. The largest environmental impact, accounting for around 73 percent of the overall result, is caused by the building mass itself. This has changed considerably in recent years, because at the turn of the millennium the operational part still dominated. However, due to the move away from fossil heating technologies during operation to renewable energy conversion technologies this changed significantly. The focus should continue to be on moving away from fossil fuels to renewable energies as this is the most feasible way forward in the first place. The often mentioned way forward for the building sector is to renovate existing buildings with an efficient building envelope, to then calculate the new heating demand in order to avoid oversizing of the renewable heating technology, and to finally install photovoltaic to produce local renewable electricity. The other option, as an alternative to locally produced renewable energy, is to draw electricity from a renewable consumer mix from the grid.

However, innovations in building materials will be even more important in the future. Most importantly for the future, buildings should be designed in such a way that they can be dismantled in a simplified manner. In this way, the concept of a circular economy of building materials can be increasingly applied. Recycled materials have the advantage that a large part of the gray energy has already been amortized and therefore a material has a significantly lower environmental impact when it enters its second life. In terms of materials, reinforced concrete showed to have the greatest environmental impact because it is used so extensively. Already today, there are concepts to reduce the amount of steel or to apply ripped structures that could even reduce the amount by about three quarters.

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Abbreviations and acronyms

AFP	Annual Performance Factor
COP	Coefficient Of Performance
CO_2	Carbon dioxide
CO_2-eq.	Carbon dioxide equivalents
eq.	Equivalents
EBP	Energiebezugsfläche
$E_{F,el}$	Electricity demand for lighting and operating equipment
EIP	Environmental Impact Points
EPD	Environmental Product Déclarations
ERA	Energy Reference Area
FU	Functional Unit
GHG	Green House Gas
GWP	Global Warming Potential
HSLU	Hochschule Luzern
ISO	International Organization for Standardization
KBOB	Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren KBOB
kg	kilogram
kWh	kilo-Watt-hour
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MFH	Multi Family House
MS	Microsoft
MRR	Maintenance, Repair, Replacement
m^2	Square meter
PSI	Paul-Scherrer-Institute
Q_H	Heat demand for space heating
$Q_{i,el}$	Internal heat inputs
Q_w	Hot water demand
SCOP	Seasonal Coefficient Of Performance
SIA	Schweizerischer Ingenieur- und Architektenverein
UBP	Umweltbelastungspunkte

1 Introduction

The combination of the growing environmental awareness and the oil crises in the 1970'ies have left a lasting rethinking of building design and the use of energy. In the context of the oil crises, the sustainability of fossil fuels has been increasingly discussed. Together with that, the building sectors fair share to the total environmental impact started to be recognized. Since then, various regulations have emerged regarding the energy performance of buildings. Today, more and more complex buildings are being created with new materials and technologies. All these efforts aim at reducing the electrical and thermal demand while maintaining the comfort of the occupants (Nygaard Rasmussen & Birgisdóttir, 2016).

The environmental awareness, and with it the most dominant concern, climate change, has led to the need to evaluate buildings in terms of their environmental impact, both for planning of new buildings and for the assessment of existing buildings.

1.1 Current situation

Today, life cycle assessments are increasingly used for environmental analyses of products, processes, and services. These take a product's entire life cycle into account, i.e., from manufacture, transport and use through to disposal. The consumption of raw materials and energy as well as the emission of harmful substances into the air, water and soil are calculated. These negative environmental impacts can be represented using various impact categories (Bundesamt für Umwelt BAFU, 2022). Due to the current problem of climate change, the Global Warming Potential (GWP) is a widely used and often applied impact category. The Intergovernmental Panel on Climate Change (IPCC) defines GWP as the relative measure of how much a greenhouse gas (GHG) contributes to global warming over a 100-year period (Abouhamad & Abu-Hamd, 2021). Another applicable category is the total environmental impact using the ecological scarcity method, which is expressed with environmental impact points (EIP, dt. UBP). This is a Swiss method, which was developed in cooperation with research, industry, and various federal agencies (KBOB, Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren et al., 2016). Nowadays, people often talk about the 2000-Watt society. This means a primary energy output of 2000 Watts per person and the emission of one ton of CO2 equivalents per person and year. To support this objective, the Swiss Society of Engineers and Architects (SIA) has published the SIA 2040 - Efficiency Path Energy. This sets targets for the building sector to achieve the 2000-Watt society. Additionally, the norm SIA 2032 - Grey Energy of Buildings further shows calculation methods to calculate the total energy consumption and the corresponding greenhouse gas emission of a building early in the planning stage (Preisig & Pfäffli, 2010, p. 2). Nowadays, various calculation tools support the impact assessment.

1.1.1 Problem description

This thesis analyses in form of a case study the environmental impact of the multi-family home (MFH) Lisa at Gschwaderstrasse 17 in Uster, Zurich, Switzerland. The building is of solid construction, consists of eight apartments and is provided with heat by a brine-water heat pump. Various information on the construction is available in terms of documentations, building plans, and photos. Assessing the MFH Lisa in terms of a case study, some operational values are assumed as standard values given by SIA norms.

The research questions, which are to be answered by this thesis work, are as follows:

- What is the total environmental impact of a multi-family building (year of construction 2020) located in Uster, Zurich?
- What are the contributions of the operational as well as the embodied environmental impact?

1.2 Project aim and objectives

The main objective of the work is to calculate the total environmental impact of the MFH Lisa in terms of GHG emissions and UBP. For this purpose, the environmental impact is divided into embodied and operational impact. In the end, it is aimed at being able to show how strongly the embodied and operational parts of a building individually contribute to the environmental impact over its entire life cycle.

For the operational impact, the heat demand for space heating is calculated and a standard value for the heat demand for hot water is assumed. For the embodied impact, the building materials are calculated based on building plans. Subsequently, their typical lifetimes are defined. Following, all values from the embodied and operational parts are quantified based on a reference unit that is determined by the secondary database that provides the environmental impact factors. After these calculations, the results are compared with specifications from norms and standards and other studies. Finally, conclusions for the building sector will be drawn from the findings.

1.3 Organization of the report

In a first part, findings from the literature research about the topic are presented. Thereafter, the methodology is presented, which discusses the methods that are used to achieve the aims and objectives of this thesis. Thereafter, the results of the environmental impact calculations are outlined. Following, the results interpretation and the comparison with norms and other studies is shown. In the end, the potential strategies and adaptions for the building sector are presented.

2 Literature review

This chapter provides information about the existing knowledge and methodology of a Life Cycle Assessment (LCA). In a first step, the concept of an LCA is explained. Consequently, the application of an LCA to the building sector is derived. Based on the existing literature, it is shown how such an assessment is defined and performed in relation to a building. Finally, the motivation for the present study and the main findings from the literature research are presented.

2.1 Life cycle assessment

An LCA is a framework, which methodologically enables to evaluate the environmental impact that a product has over its product life. There exist different timeframes to define the product life. The main goal of an LCA is to avoid or to minimize the environmental impact before it occurs. Thus, it is used as a planning or decision-making instrument. However, it is also in use to assess existing processes or products (Wagner, 2022). Oftentimes, a product is assessed over its whole life from the natural resource extraction up to and including disposal, which is defined as cradle to grave (European Environment Agency, n.d.). Another option is cradle to cradle, which analyses the product only until recycling, biodegradation, or its entrance into a new product cycle (Sustainability Guide, n.d.). Figure 1 shows the various stages with the respective considerations.

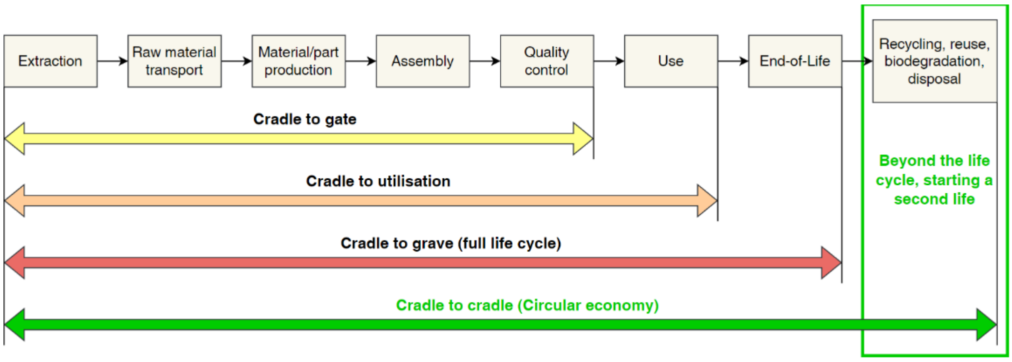

Figure 1: *Life cycle stages* (based on STAM - Mastering Excellence, n. d.)

Generally, the LCA methodology consists of a four-stage framework suggested by the International Organization for Standardization (ISO) 14040 and ISO 14044 as shown in Figure 2 (Abouhamad & Abu-Hamd, 2021). In the first phase of an LCA, the goal and scope of the study are identified. These are the objective of the research, the system boundaries, and the functional unit. The second phase, the Life Cycle Inventory (LCI), is the process of collecting data on key inputs and outputs of a product's life cycle. The third phase is the Life Cycle Impact Assessment (LCIA), which employs LCI data to estimate resource usage of the product and to analyse potential environmental impacts. In the fourth and final stage of the assessment is the interpretation. In this phase, the major issues are identified, results are addressed, and conclusions are drawn. Lastly, the limitations of the study are explained and recommendations are provided (Abd Rashid & Yusoff, 2015, p. 245).

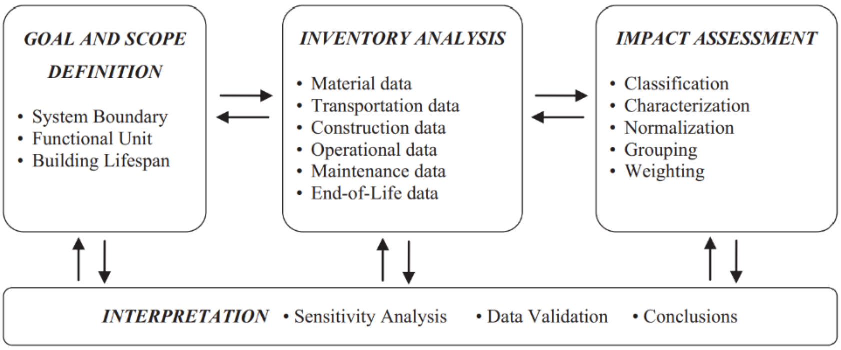

Figure 2: *Four-stage LCA framework* (Abd Rashid & Yusoff, 2015, p. 245)

The advantages of an LCA are not only environmentally but also economically. An LCA is often used for marketing and image purposes as it allows to define strategies to reduce the environmental impact of certain processes and materials by means of the resulting data. However, the drawbacks of this type of study are the complexity and subjectivity. First, there exist many different libraries of LCI. Second, for many products and processes, standardized LCI are not available. Third, based on the included data in the system boundary, the results may therefore show significant differences. Lastly, the definition of the analysis process depends on the individual who performs the study (Botejara-Antúnez et al., 2021).

2.2 Implication in building sector

This subchapter describes the application of LCA in the construction sector.

2.2.1 Growing environmental awareness

Building design and natural resource use are considerable drivers of environmental pressures on the construction industry. This is understandable when viewing recent studies, which identified that buildings on a global scale are responsible for 30-40% of energy use and 40-50% of the world's greenhouse gas emissions. This is because the building industry consists of several energy intensive and emission emitting phases like mining, manufacturing, construction, use, and demolition. While energy is consumed directly during construction, use, and demolition, it is also indirectly used when producing all types of building materials. These two types of energies are differentiated as operational energy and embodied energy (Abd Rashid & Yusoff, 2015, pp. 244–245). So to speak, every material and every process has a share of grey energy attributed to it. As one out of many industries, the construction sector is thus an evident area in which to use LCA to spot environmental problems and to promote environmentally-friendly construction (Nygaard Rasmussen & Birgisdóttir, 2016). Previous research found that the focus in the past laid on energy efficiency and emissions in the operational phase. This is understandable, because various building LCA over time have shown that for low-energy buildings, the embodied energy has a share of up to 46% of the total energy, but the operational impact continues to be the highest for conventional buildings (Anand & Amor, 2017, p. 413). This led to the development of energy efficient operation and as a result of these measures, shifted the impacts to the construction phase. Thus, as the operational phase has become more sustainable, the focus has recently turned to the embodied energy and its respective environmental impact (Anand & Amor, 2017, p. 409).

2.2.2 Relevant data

What is less clear in the current state are the calculation procedures for LCA of embodied impacts. These heavily vary depending on the country or researcher, which also lead to differing results (Abouhamad & Abu-Hamd, 2021). A study by Nwodo and Anumba (2019, as cited in Abouhamad & Abu-Hamd, 2021) found "the major challenges in building LCA to be (a) data intensity and quality, (b) subjectivity in environmental impact characterization and valuation, (c) inadequate definition of functional units, (d) assumptions for building life span and service life, (e) lack of procedures for system boundaries, (f) lack of uncertainty analysis, and (g) limitation as a decision-making tool." These uncertainties lead to the differing results between LCA studies. Therefore, care should be taken to clearly outline these aspects to understand differences when comparing different LCA studies in the same field.

An important aspect is the definition of the building lifetime, for which there are also differences across the literature with quantities like 25-50 years, 100 years, or one generation (Anand & Amor, 2017, p. 409). Research has revealed that many studies on the subject assumed a 50-year lifespan for buildings, which was found to be the average time between large retrofits during the building service life (Rodrigues & Freire, 2017, p. 561). Another aspect is the functional unit, which must be defined in an LCA. The results of the impact calculations refer to this functional unit, which ensures the correct quantification of the different products to ensure comparability with other LCA studies (Abd Rashid &

Yusoff, 2015, p. 245). Common functional units for residential buildings are square meter of useful living area, total house, volume, heat delivery, and heated floor area (Anand & Amor, 2017, p. 409). Understanding the concept of the functional unit, it becomes apparent that the previously mentioned lifetime of a building could be less relevant. This is because the impact results are broken down to this unit, which in the optimal case is a unit that is commonly used in other LCA. As a result, the energy and carbon intensity of a building can consequently be investigated in reference to the functional unit, for example as $kWh/m^2/year$ and $kgCO_2$-eq./m^2/year (Densley Tingley & Davison, 2012, p. 388).

2.3 Building definitions

The study of the environmental impact of a building requires knowledge of certain definitions. In the following, the most important definitions that occur several times throughout the thesis, are explained. First, is the Energy Reference Area (ERA, dt. EBF), which is the sum of all floor areas above and below ground, which are located within the thermal envelope of a building and for the use of which heating, or air conditioning is necessary. Floor areas with a room height of less than one meter are not included in the ERA. This area is defined in SIA 416/1 and more details are found in SIA 380. Second, is the thermal building envelope, which is composed of the components that completely enclose the conditioned spaces on all sides. Mentioned in this context, is the thermal envelope area, which represents the areas against the outside, against unheated rooms and against the ground. It is important to note that the areas against neighboring heated rooms are not included in the thermal envelope area. Third, is the heating demand, which describes the amount of heat that is required to keep the building at a desired room temperature. In the SIA norms, this is mostly given on a "per year and ERA" basis. It is calculated from the transmission and ventilation losses minus the amount of heat gains within the system boundary. The heat inputs arise from solar radiation and from heat emitted by people and electrical equipment. Finally, when calculating the heat demand, the heat transfer coefficient is also essential. It is the ratio of the density of the heat flow passing through a component to the difference between the adjacent ambient temperatures (SIA, 2016, p. 9-13).

Moreover, there are different housing standards present. In Switzerland, for example, these are the different Minergie standards (Minergie, 2022). Furthermore, the building certificate of the cantons (dt. Gebäudeenergieausweis der Kantone, GEAK) (Verein GEAK, 2022). These standards aim at planning, constructing, and evaluating buildings in an energy-efficient way to obtain certification. With that, subsidies from the federal government or canton can be claimed. To conclude, the exact values for these standards are not explained further, since it is not the focus of this thesis.

2.4 System boundary

Generally, there exist many studies that analyse embodied life cycle energy and climate change impacts, however, as previously mentioned, results differ from study to study. This is to a certain extent due to the system boundary and the considered construction materials. A study by Nygaard Rasmussen and Birgisdóttir (2016) states a low significance of the construction stage and the transport of materials to the construction site compared to the production and use stage. In a similar study, Rodrigues and Freire (2017, p. 561) disclose that the end-of-life stage, which describes the demolition and waste treatment phase, cannot be precisely predicted, but is anyway of minor importance in residential buildings with a share of only 5% of the summed life cycle impacts. Research by Basbagill et al. (2013, p. 83) advocate the previously mentioned cut-off of on-site construction and demolition. This is visualized in Figure 3, where the system boundary is depicted with dashed lines. Nonetheless, the study incorporated embodied impacts of maintenance, repair, and replacement (MRR) of building components, which come along with some difficulties due to uncertainties in the use-stage dynamics (Basbagill et al., 2013, p. 89). More modern approaches tend to incorporate the end-of-life phases for buildings because of the increasing ability to recycle building materials (Abd Rashid & Yusoff, 2015, p. 246). This was shown with a building that was analyzed in Sweden for a lifespan of 50 years. It could recover around 15% of the total energy used due to its recycling potential (Abd Rashid & Yusoff, 2015, p. 247).

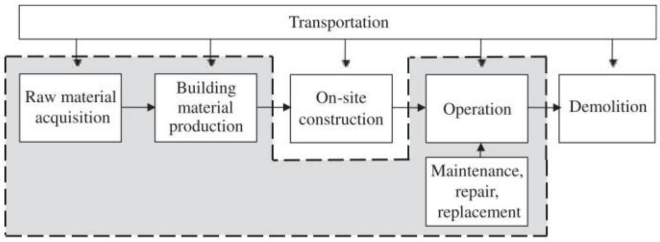

Figure 3: Potential design of a building system boundary
(Basbagill et al., 2013, p. 83)

2.5 Life cycle inventory

The LCI is the data collection part of an LCA. It includes the determination and quantification of the relevant inflows and outflows of the system. The LCI of buildings is complex because of the various processes and materials included. Even more, because of the dynamic operation of buildings, which is caused by varying user behaviour. In addition to that, there are variations in generic data from databases or Environmental Product Declarations (EPD). One explanation for this, is a missing standardization in data collection methods as previously mentioned (Anand & Amor, 2017, p. 410). The life cycle inventory can be divided into two areas. On one hand, the embodied materials and processes used in the construction of the building and its mass. On the other hand, the operational products, and processes during the use phase of the building. Fundamentally, the embodied energy as described by Dahlstrøm (2011) includes "raw material mining, building material production, transportation to construction site, building shell construction and renovation, operation energy (heating, hot water, appliances and lightning), building demolition, transport to a waste treatment plant and energy consumed at the landfill site or at the recycling plant." This is supported by Rodrigues and Freire (2017, p. 561) who add the operational energy that is "used for heating and cooling and, when applied, lighting, appliances, and ventilation". Comparing this with Figure 3 it can be observed that there are still quite a lot of similarities in the literature with some processes that are repeatedly considered.

2.5.1 KBOB database

The Coordination Conference of Building and Real Estate Bodies of Public Builders (dt. KBOB) provides a solid database for the LCA of a building. The latest version "Life Cycle Assessment Data in the Building Sector 2009/1:2022" is from 2022 and is based on the ecoinvent database of the ecoinvent center, which is composed of the ETH Zurich and Lausanne, Paul Scherrer Institute (PSI), Empa, and agroscope ART. In reference to the norm SIA 2032, it is the database for the grey energy and greenhouse gas emissions of building materials (eco-bau & KBOB, Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren, 2011, p. 1). The newly released version from 2022 renewed the building technology, certain building materials, energy supply, transport services, and disposal services. Table 1 shows the processes, materials, and considerations that are included in the individual categories. Additionally, what is not included is addressed as cut-off. From this, the precision of the database becomes apparent. Comparing the considerations in Table 1 below with Figure 3 in Chapter 2.4, one can see that both systems exclude on-site construction. However, there are differences in terms of maintenance and disposal. This illustrates the previously mentioned inconsistency between LCA studies. The material and energy flows presented in the table below are evaluated according to their environmental impact potential. One evaluation category of the KBOB database is the evaluation with the method of ecological scarcity. This is expressed with environmental impact points (EIP, dt. UBP). EIP is a Swiss method, which was elaborated by various agencies (KBOB, Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren et al., 2016).

Table 1: *System boundary of the KBOB database*

Category	Sub-category	Considerations
Building material	**Production**	Raw material sourcing
		Energy for production and transportation
		Provision and disposal of infrastructure (e.g., stone quarry)
		All emissions generated during the above phases
	Disposal	Demolition work incl. provision of process energy, transportation, and generated emissions
		Provision of infrastructure for demolition work
		Disposal in landfill or recycling
	Cut-off	Transportation starting at factory
		Processing on site
		Potential maintenance during use phase
Energy	**Final energy**	Provision of energy carriers starting from sourcing
		Provision and disposal of infrastructure (e.g., oil rig, pipelines etc.)
		All emissions generated, incl. burning of energy carriers
	Additional considerations for usable energy	Heat supply utilization rate
		Provision and disposal of heat generators
Transportation	**Transportation services**	Provision of energy carriers starting from sourcing
		Provision and disposal of infrastructure
		Vehicle utilization
		All emissions during driving, incl. noise pollution
	Passenger transport	Commuting of 13’400 km/person and year for different means of transport
	Freight transport	40 tons transported 1’000 km to construction site for different means of transport

In addition to the embodied environmental impact of the building materials, the operational environmental impact of a building can also be calculated by means of the energy data in the KBOB database. To do this, however, the heat and electricity demand of a building is necessary.

In central Switzerland, the SIA 380/1:2016 Microsoft (MS) Excel calculation program is increasingly used for this purpose. It is recognized in the cantons of central Switzerland and is used for the preparation of energy certificates. Based on the heat demand, the environmental impact of the consumed energy can be found by means of the energy data in the KBOB database (EnFK Zentralschweiz, 2021).

2.6 Life cycle impact

Available literature allows to gain some knowledge about how much the different areas of a building contribute to the environmental impact. Dahlstrøm (2011) found that generally 80-90% of the life cycle energy is attributable to the operation phase and 10-20% to the embodied energy in materials (Dahlstrøm, 2011). Most researchers come to an equal conclusion, which arises from the extensive operational duration during which a considerable amount of energy is required (Abd Rashid & Yusoff, 2015, p. 247). However, previous research found that low-energy buildings reduce the environmental impact due to lower energy consumption during the use phase (Abd Rashid & Yusoff, 2015, p. 247).
Asif et al. (2007, as cited in Abd Rashid & Yusoff, 2015, p. 247) identified the shares of the different contributors to embodied energy as follows: "concrete contributed 61% of initial embodied energy, followed by timber (13%) and ceramic tiles (14%) for a residential building in Scotland." This shows the large energy share of concrete that is expected to be of similar significance in this thesis.

2.7 Relevant findings from the literature

Literature research showed that LCA have already been applied to the construction sector. Despite this, it was found that there is still a lack of consensus on what to include within the system boundary. Interestingly, previous studies found that the operational phase contributes more to the environmental impact than the embodied part of a building. However, it was shown that this is currently changing with the implementation of efficiency measures for the operational phase. Lastly, it was found that the KBOB database provides solid secondary data and is based on the ecoinvent database.

2.8 Motivation for the present study

The aim of this thesis is to conduct an accurate LCA of a multi-family house (MFH) and to research the contribution of the embodied and the operational parts to the overall environmental impact of the building. As the literature review showed, it is difficult to identify the exact system boundaries that were used in certain studies. For this reason, the processes included in the KBOB database have already been clearly shown in Table 1 to provide clarity to the reader. Another objective is to find out whether the trend that the operational influence has recently decreased also applies to a MFH in Switzerland.

3 Methodology

This section describes the methodology and the methods that were used to arrive at the project objectives. In a first step, the LCA methodology is generically explained. This is followed by the description of the four stages of an LCA. Thereafter, the methodology is described in reference to the case study object MFH Lisa. There, the procedure that was used to obtain the required quantitative results is explained. Subsequently, the use of the KBOB database for the LCI is described. In that way, the procedure for calculating the embodied and operational environmental impact of a MFH is shown.

3.1 Life cycle assessment methodology

For the present thesis, the LCA framework according to ISO 14040 and 14044 was used, which was explained within the literature review. With the four stages of goal and scope definition, LCI, LCIA, and interpretation, the environmental impacts during the building life cycle were found. The LCA methodology was selected due to its clearly structured approach and the awareness in research and industry. In this thesis, the LCI is based on the information provided by SIA and KBOB. The KBOB database certainly offers the advantage of a standardized and relatively convenient application as the data can be accessed through a PDF file or an Excel spreadsheet.

3.1.1 Goal and scope definition

This stage defines the goal for carrying out the analysis and indicates the potential users and audience of the results. The scope defines the product or system, the functional unit, and the system boundaries. The functional unit is a quantitative measure to which the systems inputs and outputs are related to. It is of relevance to ensure comparability of the results with other LCA studies. The system boundary aims at providing an overview of the included and excluded processes (Dahlstrøm, 2011).

3.1.2 Inventory analysis

The LCI describes the data collection for the analysed system. In this stage, calculation procedures are outlined to quantify the systems relevant inputs and outputs. Once data collection for the system components is finished, the data is connected to a background inventory database. These databases offer detailed inventory data on processes and materials, which allows to access data from countless processes that are linked to the components within the system boundary. This enables for a reduction in complexity of the systems impact calculations (Dahlstrøm, 2011).

3.1.3 Impact assessment

This section of the LCA converts the results from the LCI into the different environmental impacts. There are various impact categories that can be used to express the environmental impact and the selection is based on the goal and scope of the LCA. The impact categories are divided into midpoint and endpoint levels. As an example, the midpoint impact of the global warming effect is frequently used. Here, various greenhouse gases that contribute to global warming are combined into the midpoint category Global Warming Potential (GWP). GWP ratios of various gases allow to convert these gases into equivalent amounts of CO_2. As a result, all greenhouse gases can be represented as the equivalent of CO_2 (The Guardian, 2011). GWP can lead to even further impacts such as biodiversity change or species loss, which then lead to the impact categories on the endpoint level such as damage to human health, damage to resource availability, and damage to ecosystems. Those represent the endpoint level (Dahlstrøm, 2011).

3.1.4 Interpretation

In the life cycle interpretation, the findings from the LCIA and LCI are analysed and interpreted. The results should be consistent with the goal and scope. Additionally, limitations of the study should be discussed, and a conclusion should be presented in this stage.

3.2 Case study description

This section describes the multi-family house Lisa as the case study object of the present thesis. Therefore, the functional unit and the system boundary are explained. Thereafter, the methods to calculate the inputs and outputs of the system, the LCI, is shown. Finally, it is elaborated how the results of the LCI calculations are converted into the environmental impact categories.

3.3 Multi-family house Lisa

The multi-family house Lisa has eight apartments with 2.5 to 4.5 rooms and is located at Gschwaderstrasse 17 in Uster, Zurich. The building has a flat roof and is of solid/massive construction. The interior is finished in plaster and abrasion and partly ceramic tiles in the wet rooms, whereas the exterior has a plastered facade. Further, the floors are made of parquet or ceramic tiles. Moreover, the house has plastic windows with triple insulation glazing and laminated safety glass on the first floor. The most common sanitary and electrotechnical equipment is installed. In addition, the house has underfloor heating with individual room regulation on all floors except the basement. The heat generation for space heating and hot water is done by a brine-water heat pump. Figure 4 shows various views of the building.

The energy reference area (ERA) is 1’039 m^2 and the considered service life is 60 years.

Figure 4: *Building views of MFH Lisa*

For additional technical building plans, see Appendix A.

3.4 Goal and scope

The purpose of the LCA in this thesis was to investigate the environmental impact of the MFH Lisa. The intended users of the assessment results are the Hochschule Luzern (HSLU) and industry experts. The intended use of the LCA was to compare the environmental impacts for the materials and processes of the building and to explore strategies that could lead to net-zero greenhouse gas (GHG) emissions in the construction sector by the year 2050.

The units for the building parts, technologies, and processes are listed in the KBOB database as reference unit (dt. Bezug). All of the considered inputs and outputs of the system needed to be quantified according to their respective reference.

This allowed, thereafter, the conversion into the impact categories. For this case study, EIP and kg CO_2-eq. were determined, which were used to state the results of the environmental impact. The processes that were included stem from the availability in the KBOB database as shown in Table 1, which represents a cradle to grave LCA. Moreover, the lifespan of the building was assumed with 60 years. As was shown in the literature review, many LCA building studies used 50 years. However, the document "Rules for the life cycle assessment of buildings in Switzerland", which refers to SIA 2032, states 60 years as the life span (Frischknecht, 2015). Thus, this was used as the assessment period of MFH Lisa. Any replacements of building materials within this lifetime period were considered in the impact calculations.

3.4.1 Functional unit

The functional unit of the assessment was "One year out of 60 year life span and one square meter of energy reference area of MFH Lisa for the whole life cycle with construction, replacements, operation, and disposal". Thus, all environmental impacts were broken down to this functional unit (m2 EBF and year).

3.4.2 System boundary

The system boundary was defined to incorporate the phases from cradle to grave as presented in Chapter 2.5.1. In relation to the MFH Lisa, this results in the following system boundary as shown in a simplistic manner in Figure 5. Additionally, the cut-offs are described, which were not considered in the LCI and LCIA calculations.

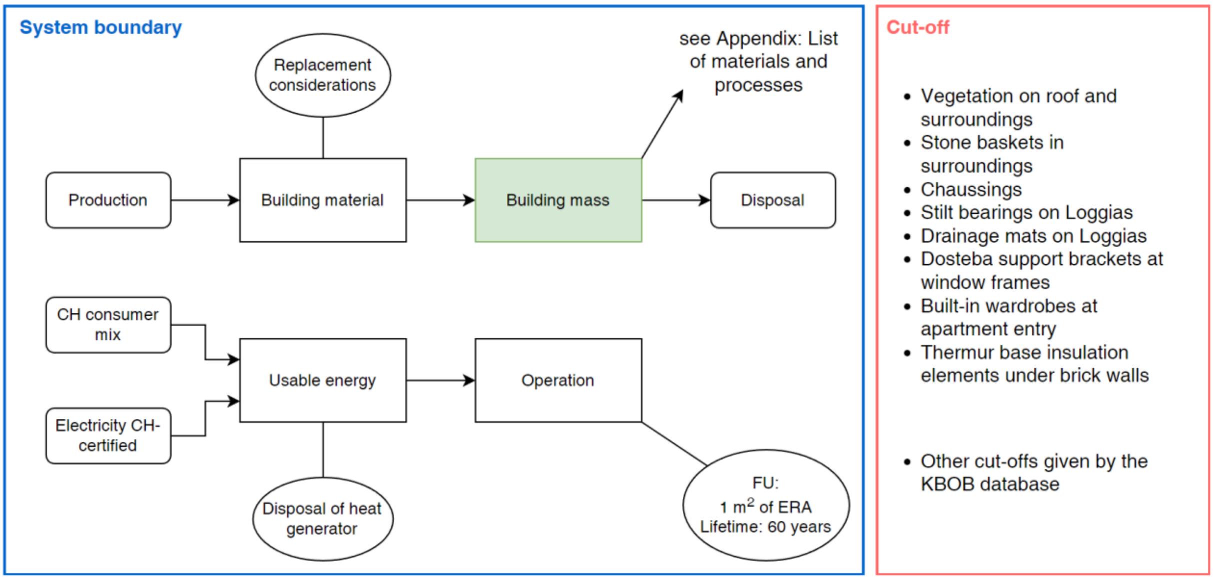

Figure 5: *Simplified system boundary for the LCA of MFH Lisa*

The building assessment is divided into two sections. One part is the embodied impact assessment that includes the building material as presented within the system boundary. These are for example the concrete, brick, parquet, or plaster, but also the building appliances and building technology. The other part is the operational impact assessment, which considered the usable energy resulting from the heat demands for space heating and hot water. The final energy was considered as well due to the consideration of the electricity demand.

3.5 Life cycle inventory

For MFH Lisa, the required primary data was obtained in various ways. For the operational data, namely the heat demand, the MS Excel calculation program for SIA 380/1:2016 was used (EnFK Zentralschweiz, 2021). It requires a relatively large effort to understand the relevant inputs.
However, the most important formulas for calculating the heat demand are stored within the tool, which shortens the own calculation steps enormously. Necessary inputs for this tool are various building data, which were collected with the Bluebeam Revu 20 building software and where necessary with information from SIA norms. The building software also required a learning effort but offered good tracking of the collected data and a highly precise measuring of building parts. For the data of the embodied parts, Bluebeam Revu 20 was used again. The building dimensions could be clearly declared by building area and material. Following, the data was exported to MS Excel for further calculations. Subsequently, the inventory was broken down to the reference in order to calculate the impact with the KBOB data. The data collection required good structuring and tracking, but this could be well ensured with MS Excel. In addition, the data could then be easily linked to the data in the KBOB database.

3.6 Life cycle impact assessment

One impact category in this thesis is kilogram of carbon dioxide equivalent (kg CO_2-eq.). The second impact category is the Environmental Impact Points (EIP), which expresses the ecological scarcity. It is a Swiss method coming from research, industry, and federal agencies (KBOB, Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren et al., 2016). The LCA database in the building sector ("Ökobilanzdaten im Baubereich 2009-1-2022") from the KBOB was used as the background inventory database from which the environmental impacts could finally be calculated. It considers state-of-the-art technologies in different areas such as recycling and is of decent detail in the description of the included processes. As a first step, the materials, and processes from the LCI needed to be calculated to the reference unit defined in the KBOB database, which was done in MS Excel. Afterwards, the environmental impacts were calculated by multiplying the impact values with the resulting reference values from the LCI.

3.7 Embodied material assessment

Various information was available for the material assessment. There is a building description, a documentation about the building, and various building plans from different perspectives. Some of the building plans have very generic descriptions, which made it difficult to identify the materials. Thus, additional photos of the construction process supported in this regard.
With the Bluebeam Revu 20 software, all building plans were first read in. With suitable software tools, the volume, mass, and number of the building parts could be measured. All dimensions had to be clearly declared in order to simplify later calculations. The measurement data could in the following be listed in the software and then imported into Excel. Afterwards, the data was divided into the various building categories within MS Excel. By importing the required impact data from the KBOB database into MS Excel, the impacts of the embodied part of MFH Lisa were calculated. These embodied impact results were expressed in UBP, and kg CO_2-eq.

3.8 Use stage assessment

For the calculation of the operational environmental impact, the specifications of the norm SIA 380/1:2016 were followed. The norm, which provides important information on the necessary inputs, is the basis for the MS Excel calculation program for SIA 380/1:2016. This tool was used to calculate the heat demand for the case study object. Figure 6 shows the system boundary of this tool. In addition, the relevant energy values are described. As can be seen in the figure, the tool records the heating demand and various internal heat losses and heat gains.
The electricity demand and the hot water heat demand had to be considered separately and were assumed with standard values from SIA 380/1:2016 as follows:

- Electricity demand $E_{F,el}$: 28 kWh / m2 ERA and one year
- Hot water heat demand: Q_w: 21 kWh / m2 ERA and one year

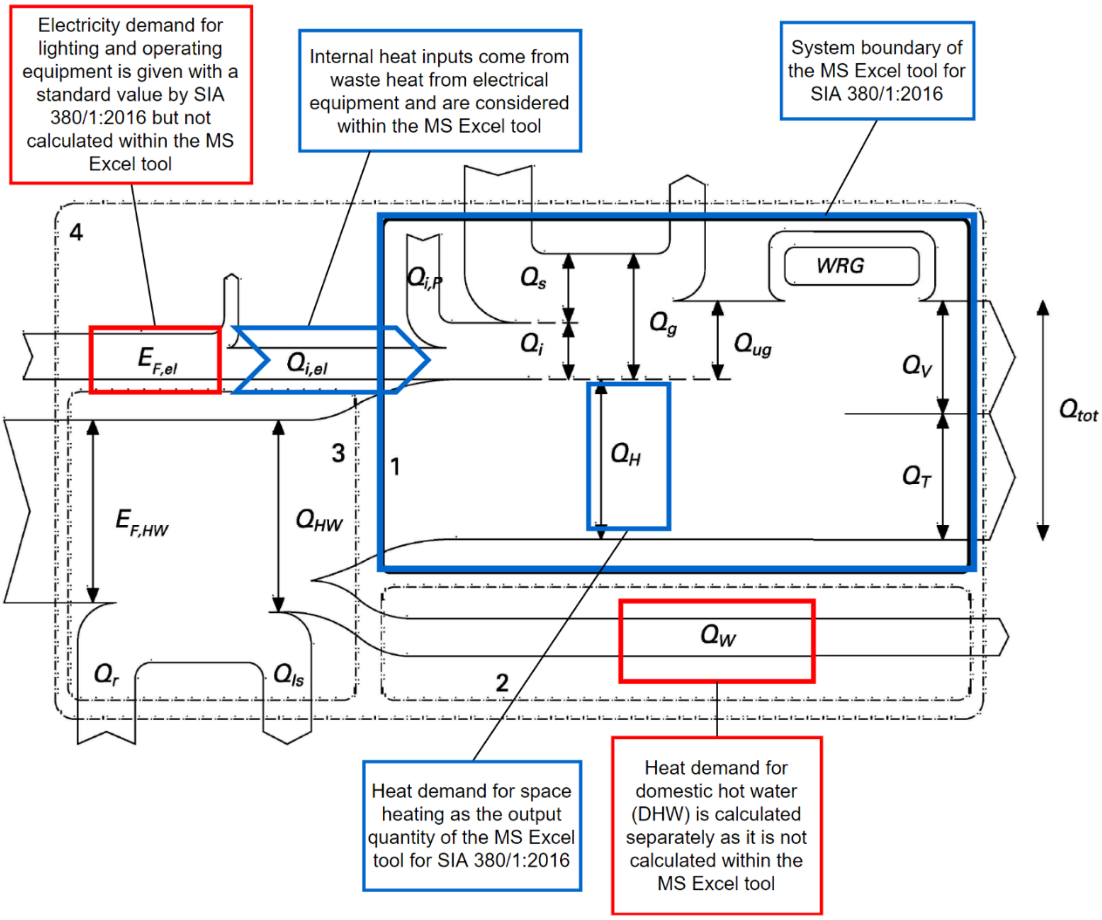

Figure 6: *System boundary for heat demand according to SIA 380/1:2016* (based on SIA, 2016, p. 8). Copyright 2016 by SIA Zurich.

The most relevant terms from the above system description are explained in the provided boxes in Figure 6. All other terms are considered of less importance to the readers understanding and are thus not further explained.

The MS Excel tool also required various building measurements regarding the building envelope. For similar reasons as explained in the previous chapter, Bluebeam Revu 20 was used.

Following the calculations with the MS Excel tool, the relevant data such as heating demand, hot water heat demand, and electricity were recorded in a separate Excel spreadsheet. Subsequently, the impact calculations were performed using the included KBOB data.
Since the coefficient of performance (COP), or the annual performance factor (AFP) of the heat pump were not known, different possible values were determined, and different cases calculated. This was done to detect a possible sensitivity of the result. Due to different COPs, different amounts of electricity are needed from the grid to supply the heat pump. Thus, it was expected that the related environmental impact will also show differences.
Finally, the impact of the electricity mixes on the result were shown. This was done to show that the electric power grid is dynamic, and therefore the operational results can also fluctuate significantly.

3.9 Life cycle interpretation

In this phase, the environmental impacts of MFH Lisa were compared. For this purpose, different comparisons regarding the impacts of different materials, building sections, building technology, and the operational phase were conducted. Important to note is that all percentage comparisons were made using the absolute figures for GHG emissions only. This is justified by the fact that GHG emissions is a frequently used impact category and makes this case study comparable with other studies. Furthermore, the presentation of all percentage comparisons in addition with EIP would clutter the thesis without showing significantly more results.

3.9.1 Embodied Life cycle interpretation

The embodied impact results were intended to be analyzed with differentiations of the building parts. Hence, the GHG emission shares were presented on one hand in relation to:

- the total of the building
- the floor levels

and on the other hand, in relation to:

- the excavation
- the raw construction
- the vertical building envelope over terrain
- the roof structure (horizontal building envelope)
- the windows and doors
- the interior finishing
- and the building technology

The insights were used to compare the results to existing norms and guidelines and to other LCA studies of buildings. Furthermore, it provided information on highly impactful materials and processes. This provided information to explore possible strategies in the construction industry to arrive at net zero greenhouse gas emissions by 2050. An ABC analysis was conducted to find the highest impacting materials and processes. This tool allowed to sort a set of values into three different classes A, B, and C. The values in these classes contribute 80, 15, and 5 percent respectively to an effect.

Mercandetti (2022) describes it in the following way:

- A parts: 10-20% of these parts cover around 80% of the analysed set
- B parts: 20-30% of these parts cover around 15%
- C parts: 50-70% of these parts cover the remaining 5%

3.9.2 Operational life cycle interpretation

The operational impact results are analyzed in terms of the individual impact contributors share to the impact. Further, the effects of different efficiencies of heat pumps will be interpreted. Finally, differences due to the electricity mix will be discussed.
MS Excel is used for all graphical representations.

4 Results

In this chapter, the results of the LCIA calculations are outlined. In the first part, the findings from the embodied life cycle impact assessment are presented. Secondly, the operational life cycle impact assessment results are shown. Following, the interpretation of the results provides further information on the relevant insights. Finally, a comparison with norms, guidelines, and other comparable studies are given.

4.1 Embodied life cycle impact assessment

This chapter describes the environmental impact of the multi-family home Lisa in terms of the embodied UBP and GHG emissions. According to the KBOB database, the embodied impact results from the environmental impact of the various building materials and building processes from production to disposal. In this database, the environmental impacts are broken down to the reference units kg, m^2, and m^3. Using the Bluebeam Revu 20 planning software, the predefined building parts were measured and calculated according to the necessary reference unit to subsequently determine the environmental impacts. The different lifetimes of building materials mean that certain parts of the building, throughout the building's 60-year life, will need to be replaced in between. These replacements were considered in the calculations. In the following, the embodied environmental impact results are explained in more detail.

4.1.1 Overall embodied building impact

The first analysis dealt with the overall impact of the sum of all parts of the building over the building lifetime of 60 years. This includes the preparatory work, namely the excavation, the building parts of the carcass (raw construction), as well as the interior fittings.
Table 2 shows the UBP and GHG emissions in kg CO_2-eq. for the whole building. For comparisons and for a better tangibility of the result, the influences are also given in relation to the ERA of the MFH Lisa of 1’039 m^2. In addition, the results are provided per ERA and one year, broken down from a total building impact amortization time of 60 years.

Table 2: *Embodied environmental impact results*

Position	Embodied environmental impact	
1	Total building EIP	1’613’439’912.06
2	Total building GHG emissions in kg CO_2-eq.	917’723.09
	Embodied environmental impact per ERA	
3	Total building EIP / ERA	1’552’877.68
4	Total building GHG emissions in kg CO_2-eq. / ERA	883.28
	Embodied environmental impact per ERA and year	
5	Total building EIP / ERA*a	25’881.29
6	**Total building GHG emissions in kg CO_2-eq. / ERA*a**	**14.72**

4.1.2 Embodied impact differentiation

What is more revealing than the results in Table 2, is an understanding of the embodied environmental impact of the different floor levels, construction forms, individual building materials, and the building technology. Thus, this subchapter describes the impact differentiation for certain building categories.

The shares of the individual building components to the GHG emissions are illustrated in Figure 7. It represents all building materials, building technology, appliances, and processes. As shown, the share of normal concrete largely surpasses all other building components. It reaches a share of around 47 percent, while none of the other data entries exceeds five percent. It is important to mention that the percentage values for these materials are based on their actual existing reference unit amount within the system boundary of the case study for MFH Lisa. This allows to see the environmental impact based on the actual total building mass. A normalization in this case is rather complex due to the different reference units given by the KBOB database and would thus distort the insight.

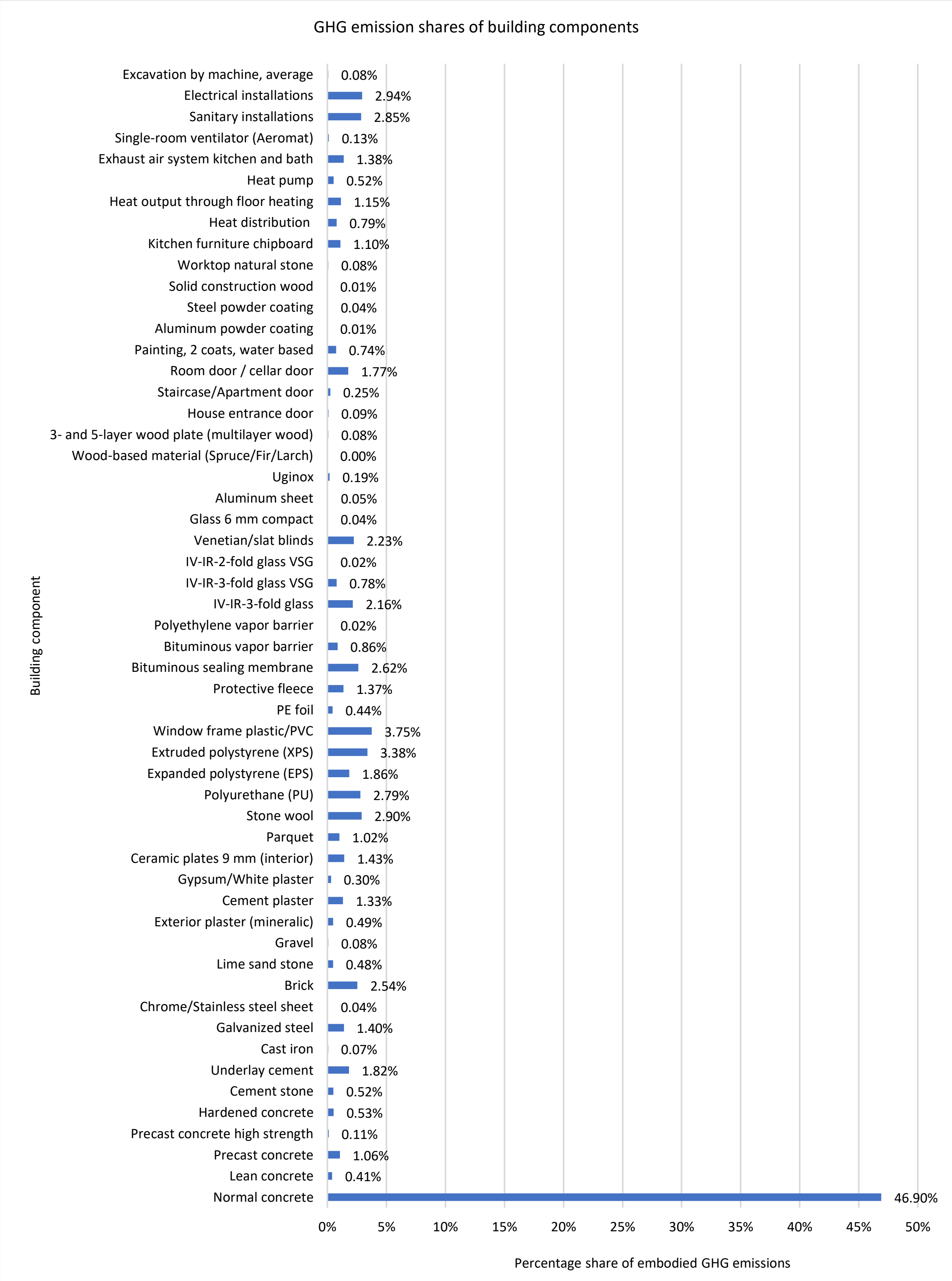

Figure 7: *Embodied GHG emission comparison of building materials and appliances in percent*

As shown in the graph above, “Normal concrete” was assumed for the reinforced concrete of MFH Lisa. This definition equals the definition of precast concrete in the KBOB database. Important to understand, is that precast concrete elements from the factory are in the context of this case study assumed to contain reinforcing steel to a similar degree as reinforced concrete created on site. Thus, the impact share of normal concrete shown in the graph (Figure 7) is made up from the combination of concrete and reinforcing steel. The KBOB database also declares structural concrete without reinforcement. Therefore, depending on the concrete type, differences in the impact result may occur. Due to this sensitivity and considering the large influence of concrete on the overall result, it was decided that the differences should be analyzed. For this reason, the volume of reinforced concrete was divided into the shares of structural concrete and the shares of reinforcing steel. According to the KBOB database, the density of the structural concrete without reinforcement is 2’300 kg/m^3 and that of reinforcing steel 7’850 kg/m^3. The steel content depends on building statics, it is, however, in this context assumed to be in one case 100 kg steel per m^3 of concrete (Sedlak, 2022) and in another case 170 kg steel per m^3 concrete (holzvonhier, 2016). Using the densities, the masses for concrete and steel could be calculated separately.

Figure 8 visualizes the differences in GHG emissions depending on the concrete type. The concrete emissions are shown over the overall building, namely with a concrete volume of 844 m^3. As the chart shows, the impact of the concrete depends to a remarkable extent on the steel content per cubic meter of concrete. The second interesting observation is that normal concrete, which according to the KBOB database also represents precast concrete from the factory, has about the same impact as reinforced concrete with 170 kg of steel per cubic meter of concrete. This shows that precast concrete elements probably have about this steel content. It further reveals that this steel content is probably common practice and thus, with certain caution, normal concrete can be realistically assumed in the present calculations as reinforced concrete poured on site.

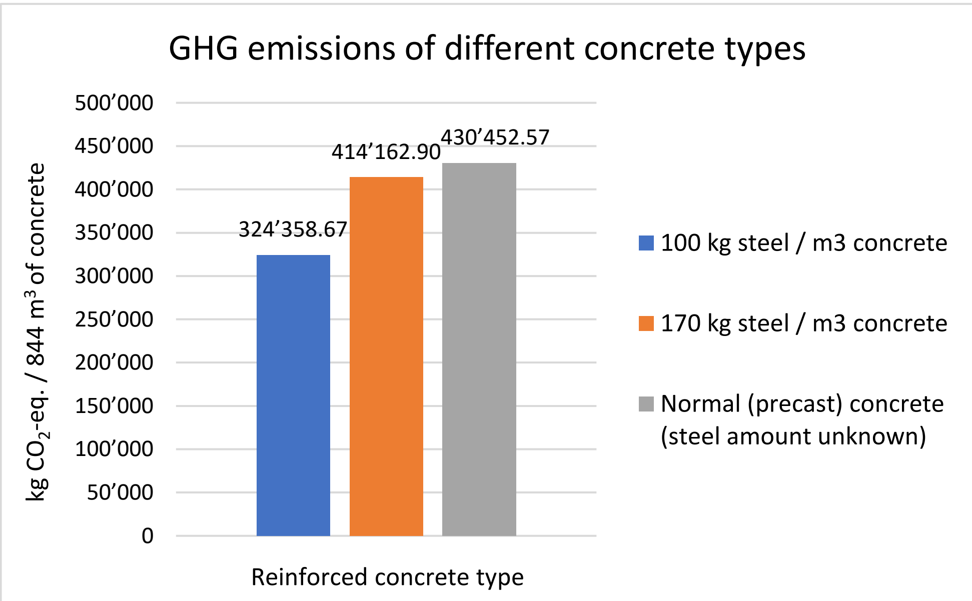

Figure 8: *Embodied GHG emissions of reinforced concrete based on reinforcement degree*

Having shown the differences in the GHG emission impacts depending on the concrete type, Figure 9 illustrates the result this has on the impact share in comparison to the other building components. As shown previously, normal concrete has an impact share of around 47% (Figure 7). However, when changing the steel content, the overall GHG impact share of reinforced concrete drastically changes to around 40% out of all building components.

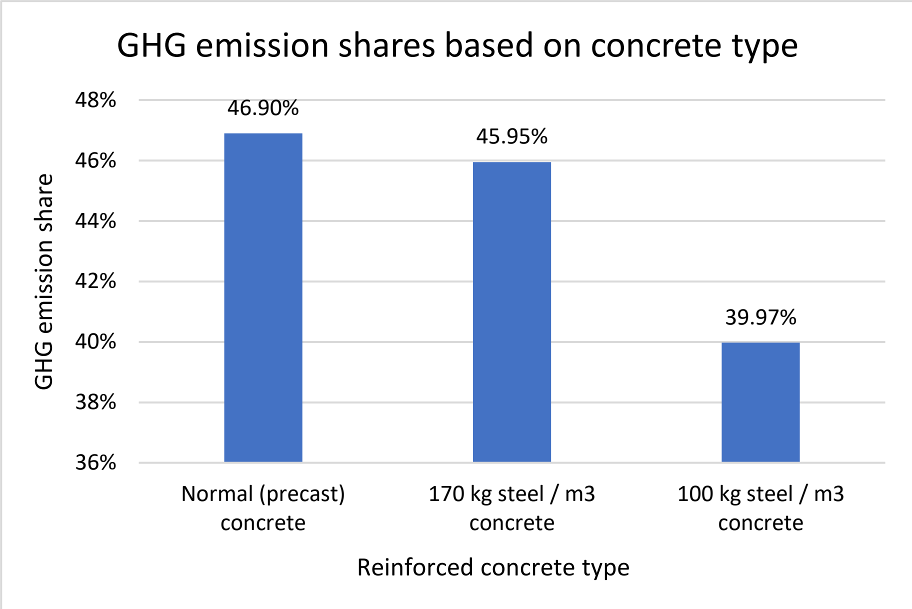

Figure 9: *Share of reinforced concrete to total embodied GHG emissions*

Even more interesting to see is the impact share of structural/high-rise concrete and reinforcing steel individually. In Figure 10 the three different concrete types are presented. The steel content for normal concrete is not declared in the KBOB database, and thus, not known as described beforehand. The figure shows that with higher steel content in reinforced concrete, the GHG emission impact share of steel exceeds the one of concrete slightly with around 53 percent. This can be explained by the high environmental impact of the steel production. Per kilogram, the environmental impact of reinforcing steel according to EIP and GHG emissions is 19 and 15 times higher, respectively, than that of structural concrete. The KBOB database attributes 99 percent of the environmental impact of reinforcing steel in terms of UBP and GHG emissions to production. There is almost no environmental impact from disposal. In the case of structural concrete, the environmental impact of production, according to UBP, is 77 percent and for normal concrete 90 percent. To conclude, disposal of these major impact materials is therefore less problematic than production.

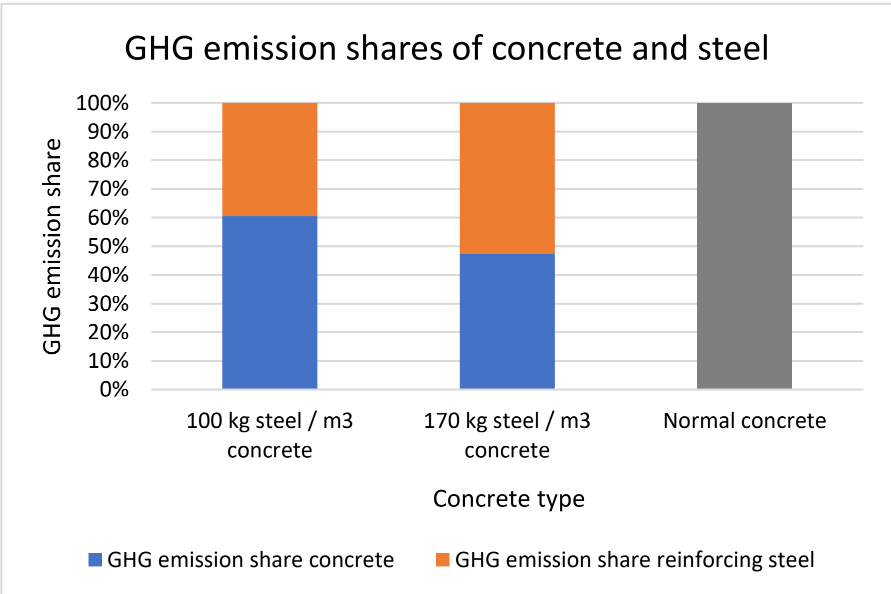

Figure 10: *Embodied GHG emission comparison of concrete and reinforcing steel*

In a further step, the environmental impacts were divided into certain categories to find out more precisely which materials and where on the building the impacts are particularly striking. Figure 11 shows the percentage share of the various building sections in reference to the overall GHG emissions of the building. What stands out from the figure is the relatively higher GHG emission share of the underground and the earth level building sections. This can be explained by the larger area of the basement and earth level compared to the upper floors, and thus, due to the large proportion of reinforced concrete in these sections. As shown, the upper floors have a similar impact share, while the share of the roof construction and the façade, which make up the building envelope, is significantly lower compared to the other building sections. This was expected as the reinforced concrete walls were allocated to the floor levels and not the building envelope. Further, the floor levels include all the interior fittings. In conclusion, the environmental impact of the building envelope is comparably low in contrast to building sections that incorporate large amounts of reinforced concrete.

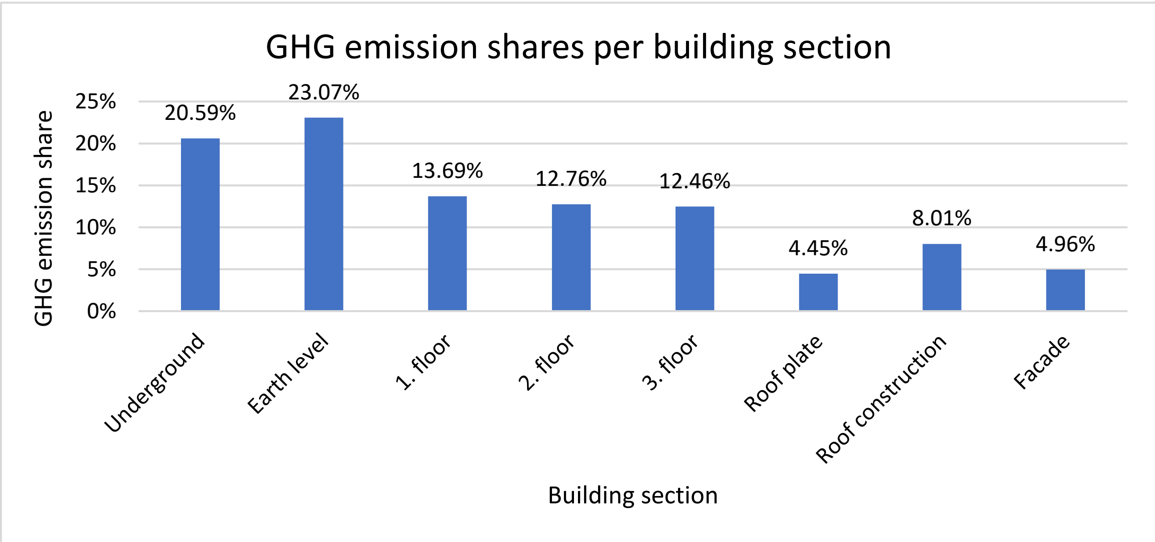

Figure 11: *Embodied GHG emission shares per building section*

Turning now to the impact comparison of the building components, Figure 12 visualizes the contribution to GHG emissions of the different parts that make up the overall building. As can be seen in the picture, the raw construction, which consists mainly of the various concrete elements, brick, and lime sandstone, accounts for over half of the embodied GHG emissions. The second highest embodied impact is caused by the building envelope, which consists of the insulation, waterproofing, protective coatings, plastering, and exterior painting. It is important to mention that this also includes the insulation and waterproofing on the outside of the garage. Due to the large area of bituminous sealing and XPS on the exterior of the garage, this has a significant impact on the proportion of the building envelope. In third place comes the interior finishing, which includes the construction of floors, walls, ceilings, and kitchen fittings. Windows and doors have a similarly large influence. The other components show smaller shares, and the excavation is surprisingly small with 0.08 percent and not recognizable anymore in the graphic.

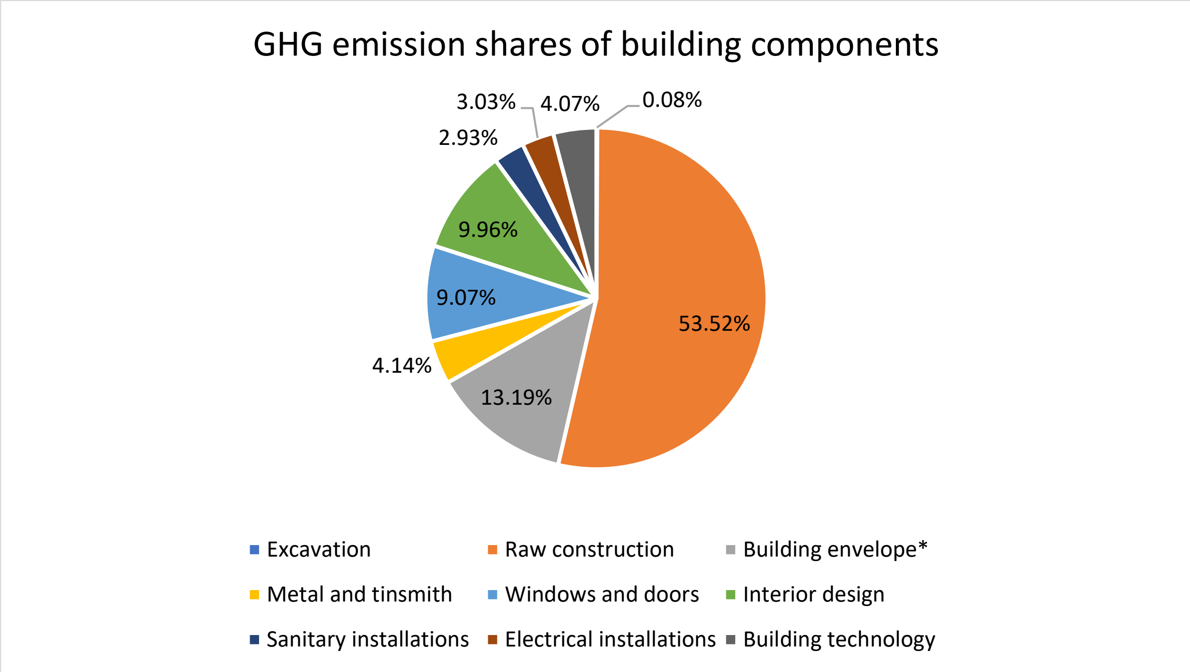

Figure 12: *Embodied impact comparison of building components*
*including major exterior areas that are insulated and sealed, namely the Earth level floor plate, walls, and the roof, excluding the sealing of the Loggia plates

To identify which building materials should receive the greatest focus for potential change in terms of environmental impact, an ABC analysis was conducted. It sorts the building parts into three different classes as explained in the methodology chapter 3.9.1. The most interesting class is the A-class, which is made up of the parts that generate around 80 percent of all embodied GHG emissions. The insight the tool creates, allows to understand which parts should receive the highest priority in assessing potential changes regarding their environmental impact. Figure 13 shows the most impactful building materials with the accumulated percentages up to but just under 80 percent. Once more, the dominance of normal concrete is observable.

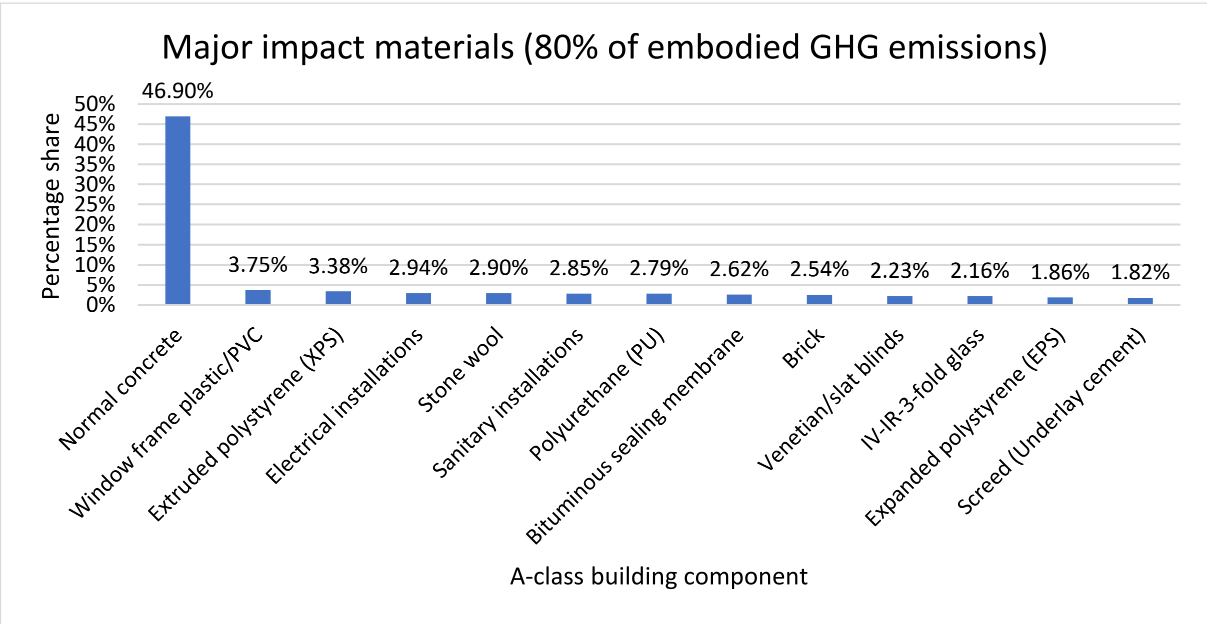

Figure 13: *Major impact materials*

4.2 Operational life cycle impact assessment

The following part of the thesis deals with the environmental impact of the building during the operational phase. In a first step, the results of the calculations of the heating demand using the SIA 380/1-2016 tool are explained. Thereafter, the environmental impact of said heating demand is shown. As in the previous chapter, the results are presented with EIP and GHG emissions over a 60 year usage phase of the building.

Central to the calculations of the environmental impact during the operational phase of the building is the brine/water heat pump, which provides for space heating and hot water production in the MFH Lisa. On pictures of the interior of the building, a Thermalia twin heat pump from the company Hoval can be seen. For calculations with heat pumps, the efficiencies of these appliances must be known. For the calculations, various values are used, which are explained in the following list:

- Coefficient of performance (COP): Laboratory measured efficiency of a heat pump at a given operating condition
- Seasonal coefficient of performance (SCOP): Laboratory measured efficiency for various operating points during the four seasons of the year
- Annual performance factor (APF, dt. JAZ): Effective efficiency of a heat pump in real conditions over one year

Table 3 shows various efficiency values that were defined through data from various sources. As presented in the table, the efficiencies of the heat pump in the production of space heat are different to the ones for domestic hot water production. This is due to the different temperature lifts the heat pump must perform from its source temperature (sole) to its supply temperature. The supply temperature for space heating is considered with 35° Celsius (Bosch Thermotechnik GmbH, 2022a), which is todays allowed maximum in Switzerland (Eyer, 2021, p. 29), while it is 55° Celsius for hot water. A higher temperature lift decreases the efficiency of the heat pump, which can be observed in the table below. The hot water temperature is given in correspondence with data from Hoval. It is commonly recommended to heat up hot water to 60°C due to hygienic reasons, but 55°C is not uncommon (S. Weber Sanitär Heizung GmbH, 2020). Thus, it is considered as such in the following calculations. Important to mention is that for Case 3, values from the outdated norm SIA 380/1:2009 (2009, pp. 50–51) were considered as the new norm SIA 380/1:2016 does not incorporate hot water production anymore. Thus, the given efficiencies are most probably outdated. For this reason, the best values were considered to calculate the COP. In addition, the old norm for water heating only specifies an air-to-water heat pump, which has lower efficiencies than ground-source heat pumps.

Table 3: *Different efficiency cases for the heat pump in operation*

Case	COP	SCOP	APF	Comments	Source
Base Case	Not specified	Not specified	5.3 (assumed for space heating + hot water production)	The base case refers to the sole/water heat pump provided in the KBOB database	(KBOB, Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren, 2022)
Case 2	4.79	Not specified	Total: 4.5 Space heating: 5.5 Hot water: 3.7	Technical data from Hoval as input to the JAZ-Rechner	(Hoval, 2022) (Bundesverband Wärmepumpe (BWP) e.V, 2022)

Case 3	Not specified	Not specified	3.94 (combined APF for space heating + hot water production)	Due to the norm being outdated, the best efficiencies were considered	(SIA, 2009, pp. 50–51)
Case 4	Not specified	Not specified	Space heating: 5.3 Hot water: 3.57	Interpolated as APF of hot water being 67% of APF of space heating as in Case 2	(KBOB, Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren, 2022)

It can be seen from the data in Table 4 that the operational environmental impact per energy reference area (ERA, dt. EBF) varies between 2’300.10 and 3’770.10 UBP / EBF and year and 0.81 and 1.91 kg of CO2-eq. / EBF and year. As it was expected, and herewith confirmed, the impact positively correlates with the annual performance factor of the heat pump. In particular, hot water production, which accounts for 46.6 percent of the heat demand in the MFH Lisa based on standard usage data (SIA, 2009, p. 44), increases the environmental impact. This is since the efficiency of the heat pump is lower for hot water production, more electrical input energy is required.

Table 4: *Operational environmental impact without considering ventilation systems and heat recovery*

Impact categories	**Base Case**	**Case 2**	**Case 3**	**Case 4**
Without ventilation systems with heat recovery				
Operational environmental impact				
Total operational EIP	1’038’839’994.0	1180638558	1’213’155’102.0	1’130’479’794.0
Total operational GHG emissions in kg CO_2-eq.	268’797.61	387153.8424	404’313.55	337’003.81
Operational environmental impact per ERA				
EIP / m^2 ERA	999’846.00	1136322	1’167’618.00	1’088’046.00
GHG emissions / m^2 ERA	258.71	372.6216	389.14	324.35
Operational environmental impact per ERA and year				
EIP / m^2 EBF*a	16’664.10	18938.7	19’460.30	18’134.10
GHG emissions / m^2 ERA*a	**4.31**	**6.21036**	**6.49**	**5.41**

It is important to note that the base case uses the latest KBOB data from 2022, which includes the new UBP from 2021 (UBP'21). These are different from the UBP of 2013, which are listed in the KBOB database from 2016. For the other cases 2 to 3 and partly also 4, the treeze heat pump calculator (treeze Ltd., 2017) was needed to calculate specific data based on the different APFs (Table 3). However, at the time of this thesis, the treeze calculator still relies on the KBOB life cycle inventory v2.2:2016 (ecoinvent v2.2). Due to these uncertainties, the four cases were introduced, which allow to see different impact results depending on different heat pump performance factors. Case 2 is considered to be an exaggeration of the negative operational impact due to the rather outdated input data from the treeze calculator. Case 3 is also considered to be an exaggeration as most heat pumps today, especially for space heating, operate at a higher APF than 3.94 (Bosch Thermotechnik GmbH, 2022b). As Case 4 splits the APF given by the KBOB database into the APF for space heating and the APF for hot water, it can be considered as a more detailed approach compared to the base case. Therefore, Case 4 is the result considered in the further calculations.

In addition to the above calculations, further calculations were carried out, which consider the nine single ventilation systems (Siegenia Aeromat VT WRG) with heat recovery in the MFH Lisa. For energy verifications based on standard use, the effects of ventilation systems are not considered, since requirements for the heating demand are basically requirements for the building. Since the ventilation systems reduce the heating demand and thus the required energy, it makes sense in the context of this thesis to show the effects on the environmental impact. Table 5 shows that the negative environmental impact decreases due to the lower energy demand, which results from the heat recovery. Equally as before, Case 4 is considered to be the most accurate result and is thus used in the further interpretation of the results. In terms of Case 4, this means that with the heat recovery, the operational GHG emission impact decreases by another 8.17% compared to without heat recovery.

Table 5: *Operational environmental impact when considering ventilation systems and heat recovery*

Impact categories	**Base Case**	**Case 2**	**Case 3**	**Case 4**
With ventilation systems with heat recovery				
Operational environmental impact				
Total operational EIP	1’013’437’067.40	1’137’304’153.80	1’156’870’186.20	1’105’076’867.40
Total operational GHG emissions in kg CO_2-eq.	259’831.87	360’953.96	371’339.56	328’038.07
Operational environmental impact per ERA				
EIP / m^2 ERA	975’396.60	1’094’614.20	1’113’445.80	1’063’596.60
GHG emissions / m^2 ERA	250.08	347.41	357.40	315.72
Operational environmental impact per ERA and year				
EIP / m^2 ERA*a	16’256.61	18’243.57	18’557.43	17’726.61
GHG emissions / m^2 ERA*a	**4.17**	**5.79**	**5.96**	**5.26**

4.3 Life cycle interpretation

This subchapter deals with the interpretation of the life cycle impact assessment results. The environmental impacts of the building materials and the operational part are analyzed to show which area contributes how much to the environmental impact.
Table 6 summarizes the environmental impact results in GHG emissions (kg CO2-eq.) and UBP over the energy reference area of 1’039 m2 and one year.

Table 6: *Total environmental impact results of MFH Lisa*

Impact category	**Without ventilation and heat recovery systems**	**With ventilation and heat recovery systems**
Embodied GHG emissions / m^2 ERA*a	14.72	14.72
Operational GHG emissions / m^2 ERA*a	5.41	5.26
Sum (kg CO_2-eq. / m^2 ERA*a	**20.13**	**19.98**
Embodied EIP / m^2 ERA*a	25’881.29	25’881.29
Operational EIP / m^2 ERA*a	18’134.10	17’726.61
Sum (EIP / m2 ERA*a)	**44’015.39**	**43’607.9**

The embodied impact assessment showed that reinforced concrete has the largest environmental impact and accounts for about 47 percent of GHG emissions compared to all building materials in the MFH Lisa. In terms of EIP, concrete has a similarly dominant value of about 43 percent. Therefore, the priority of the building sector should certainly be to make this building material more sustainable. However, as the ABC analysis revealed, there are other materials that should be treated with importance. These account for about 32 percent, as was shown in the A-materials graph in Figure 13.

The comparison of the impact share of the embodied GHG emissions and the operational GHG emissions for the MFH Lisa is set out in Figure 14. As the graph illustrates, when either neglecting the ventilation systems with heat recovery, or considering it, the impact share of the embodied GHG emissions largely exceeds the operational GHG emissions with a share of around 73.14 percent and 73.67 percent respectively. This means that around 73 percent of the total environmental impact of the MFH Lisa over a 60 year life span can be attributed to the materials, appliances, and building technology of the building. The highest impact share of the operational contributors comes from the electricity, which was calculated in reference to the Swiss electricity consumer mix 2022 of the KBOB database.

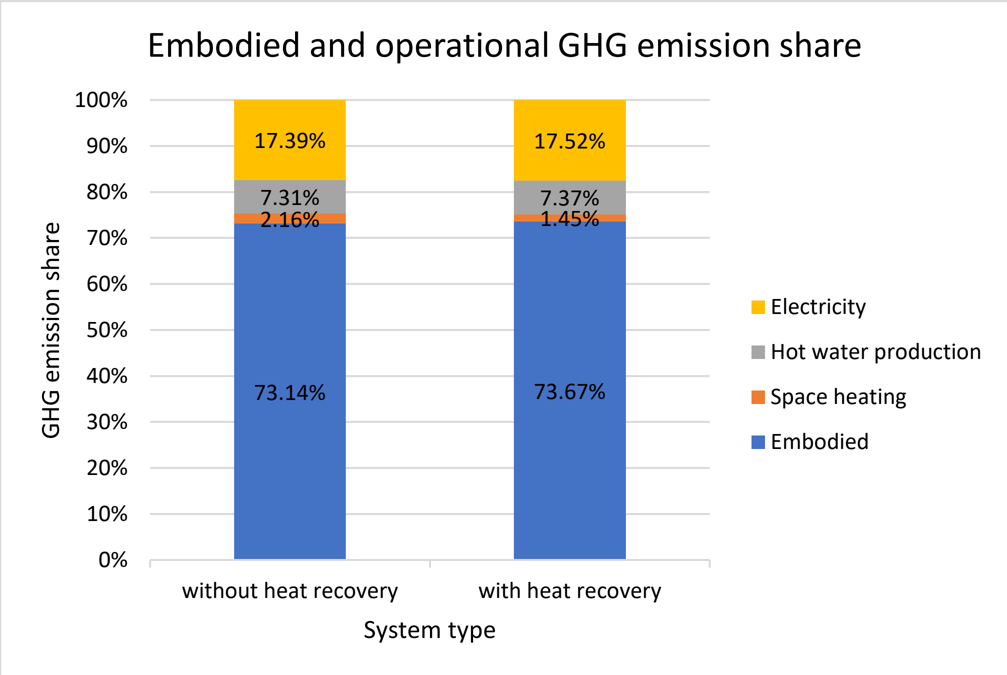

Figure 14: *Embodied and operational impact comparison*

As shown in the figure above, the heat production for hot water outnumbers the one for space heating, despite the fact that the heat demand in these two categories does not differ heavily. An explanation for this is the different COPs of the heat pump in the production of hot water and space heating. A lower COP with the hot water production leads to a higher electricity demand, which results in a higher environmental impact. The operational results must be interpreted with some caution because on one hand mostly standardized values defined by SIA were considered, and the user behavior during the operational phase influences the heat and electricity demand. Even more, the Swiss and European electricity mix and with it the consumer mix are subject to change in the future.

This circumstance has led to research into what a fully renewable consumer mix would change during the operational phase. Figure 15 shows on one side the impact shares with the current CH consumer mix and on the other side, the same system for a fully renewable consumer mix. Both systems are without ventilation and heat recovery. As shown previously, whether ventilation with heat recovery is considered, or not, does not make much of a difference. Therefore, only one system is assumed in this comparison.

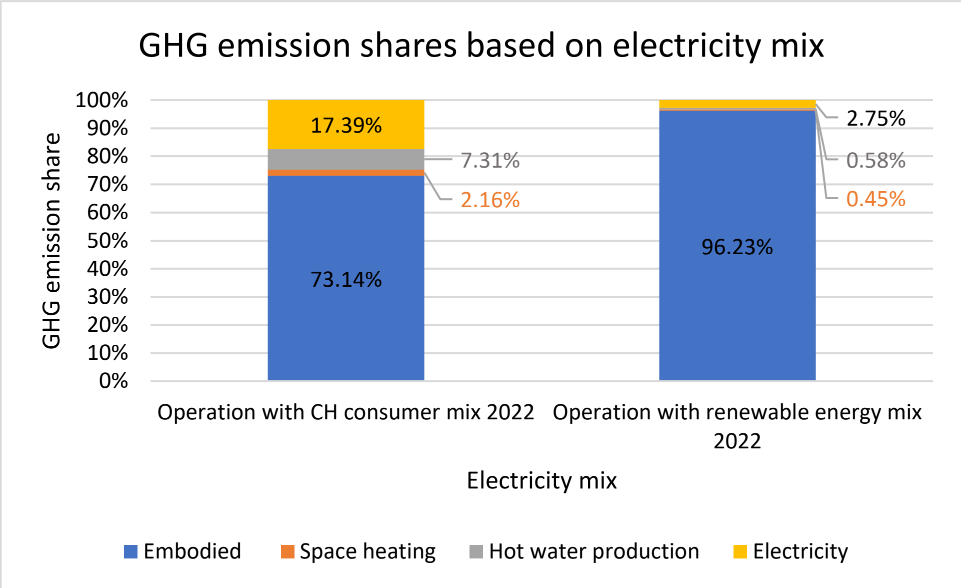

Figure 15: *Impact comparison based on different electricity mixes in use phase*

As shown in Figure 15, a renewable energy mix drastically decreases the operational environmental impact of MFH Lisa. In such a scenario, the embodied environmental impact would make up around 96 percent of the total impact of the building. It is, however, crucial to mention that the energy that is considered in the materials and processes in the KBOB database are manufacturer-specific and can vary. A transition towards a fully renewable energy system would of course also positively affect the embodied impact. Especially, future building material replacements would result in a lower environmental impact. However, as most of the embodied impact occurs up until the start of the operational phase, the presented results provide an accurate representation for the MFH Lisa.
In conclusion, despite the replacement of certain building materials and appliances in the future, the embodied impact provides a less dynamic insight compared to the operational part. Moreover, given the precise material calculations in this thesis work, these results can be interpreted as quite accurate.

4.4 Comparison with literature

A comparison of different studies is outlined in Table 7 The result of the present thesis is given in the first entry, and it shows the operational impact with heat recovery systems (HRS) and without heat recovery systems (w/o HRS). Additionally, a rating describes how MFH Lisa performs in comparison to the other listed studies and norms. All studies listed below are comparable to MFH Lisa due to the same functional unit. This, however, with an important consideration. One has to note that there are some uncertainties regarding international studies due to the fact that the energy reference area (ERA, dt. EBF) is not broadly mentioned internationally. Some studies refer to the useful living area, which of course can differ from the energy reference area that is used especially in European and Swiss studies. Values from norms presented in the table below are referencing to medium-sized residential buildings with a compact building form, a reasonable amount of windows, and a reasonable construction method with reasonable spans of the floor plates (Pfäffli & Preisig, 2017, p. 16).

Table 7: *Comparison of MFH Lisa with norms and studies*

Study or Norm	**Embodied impact [kg CO2-eq. / EBF*a]**	**Operational impact [kg CO2-eq. / EBF*a]**
Present thesis (MFH Lisa)	14.72	5.26 (HRS) 5.41 (w/o HRS)
Building example of SIA 2032 (SIA, 2010, p. 26)	8.4	5.5 Gas heating system
Swiss residential building average of buildings built in 2010 (Pfäffli & Preisig, 2017, p. 14)	10.8	33.8 (70% of heating systems used fossil fuel and had old insulation standards in 2010)
SIA Efficiency path 2040 (2011 edition)	8.5 (New buildings) 5 (Retrofitted buildings)	2.5 (New building) 5 (Retrofitted buildings)
Documentation for SIA 2040 (2017 edition) (Pfäffli & Preisig, 2017, p. 16-17)	Guideline values: 9 (New buildings) 5 (Retrofitted buildings) Desired value: 2.8 (current average: 10.8)	Guideline values: 2 (New buildings) 5 (Retrofitted buildings) Desired value: 8.7 (current average: 33.8)
Residential building complex Hüttengraben, Küsnacht, Switzerland (Pfäffli & Preisig, 2017, p. 34)	8.4	2.5 Brine-water heat pump and PV
MFH Segantinistrasse, Zurich **(retrofitted building)** (Pfäffli & Preisig, 2017, p. 41)	6.9	**0.0** Geoth. Heat pump, solar thermal, and PV (**Electricity from PV on the roof accounts for** **-3.3** and fully compensates for other operational impacts)
High-rise residential building Sihlweid, Zurich-Leimbach **(retrofitted building)** (Pfäffli & Preisig, 2017, p. 43)	5.5	4.1 Pellets heating system and PV
Case study in Toronto, Canada (Norman et al., 2006, as cited in Dahlstrøm, 2011)	7.4 (Suburban building) 9.1 (Urban building) (Both houses consist of a wooden structure and brick façade)	33.9 (Suburban building) 35.1 (Urban building) (Burning of fuel and use of electricity; data corresponds to Canada wide averages for 1997)
TEK07 building (house standard) at Stord, Norway (Dahlstrøm, 2011)	7.68	24.32 Electric heating system, Nordel low voltage mix
Passive house at Stord, Norway (Dahlstrøm, 2011)	8.58	17.42 Electric heating system, Nordel low voltage mix

Figure 16 visualizes the comparison of MFH Lisa to the norms and studies presented in the previous Table. What stands out from the graph is the relatively higher embodied environmental impact of MFH Lisa. However, regarding the operational environmental impact, MFH Lisa performs in the range of most of the SIA presented examples or desired values.

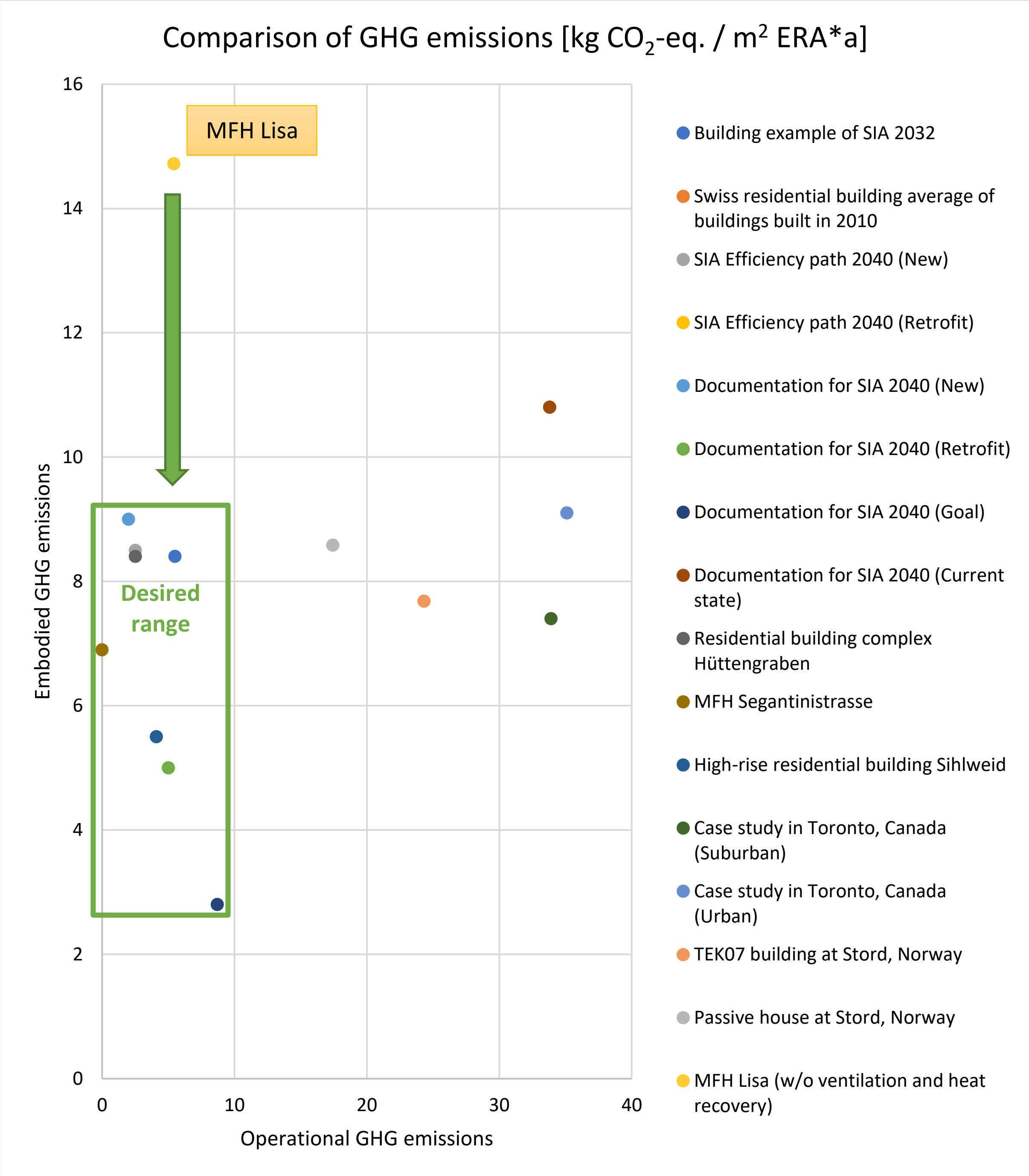

Figure 16: *Visual representation of the comparison of MFH Lisa to norms and studies*

It is apparent from the graph and consistent with previous results that the building design contributes quite strongly to the environmental impact the building. As expected from a new building built in 2020, the operational environmental impact is relatively well classified due to the thermally efficient building envelope and renewable heat generation. However, the problem lies in the massive construction, which meant that a lot of reinforced concrete was used. This drives the embodied environmental impact sharply upwards. Also clearly visible are the buildings, which are shown on the right side of the graph. These have inefficient building envelopes and non-renewable energy technologies.

5 Strategies for the construction sector

Another goal of this thesis was to show how the building sector can achieve net zero greenhouse gas emissions by 2050. Based on the results found and various concepts that can lead to a more sustainable construction sector, this chapter shows which methods or strategies the construction sector should apply to achieve this. One has to understand that net zero does not mean no greenhouse gas emissions at all, but it means that certain materials or processes should compensate for the emissions that occur during the whole life cycle of a building.

5.1 Reduction of embodied environmental impacts

For the embodied part of a building, there are already various approaches to becoming more sustainable. For Switzerland, the SIA efficiency path 2040 provides the foundation on how to build in the sense of the 2000-Watt society (2000 Watt per person) (SIA, 2011, p. 4). One theme is to construct buildings in such a way that they can be deconstructed in a simplified way. The additional costs for this could be justified by the fact that future carbon taxes and policies will increase the value of such properties, because the reusable building materials can be sold to a new building constructor. As a result, the new building constructor has a better greenhouse gas emissions balance and therefore has to pay less taxes (Densley Tingley & Davison, 2012, p. 388). This makes sense for new buildings because due to the increased use of concrete and steel, thick insulations, large window areas, and expansion of building technology appliances, new buildings are much more energy intensive than the existing building stock of Switzerland (Pfäffli & Preisig, 2017, p. 14). Using recycled material could compensate some of these materials' environmental impacts. There are already examples of buildings that have been designed for simplified deconstruction. For this, glue and screws are not used, but rather dovetail joints (timber wedging) are applied for fixation purposes (Vaillant, 2022). Ürge-Vorsatz et al. (2020) states another point from an economic perspective that maximizing operational efficiency and minimizing embodied carbon in buildings is the most cost-effective way to reduce emissions. Even more, the increase in recycling and reusage rates of building materials will reduce the extraction rate of natural resources. This allows to move towards a circular economy by closing the material loop, which is a crucial sustainability strategy (Densley Tingley & Davison, 2012, p. 388).

5.1.1 Replacement building versus retrofit

Another consideration is the service life of a building and thus the question whether new buildings or retrofits are better for the environment. A study by Rauf and Crawford (2015, p. 146) concludes that despite the additional embodied energy needs that come with replacements of building parts, the longer a building lasts, the lower is the embodied life cycle energy demand and environmental impact per year. This is because the initial embodied energy demand can be amortized over more years the longer the building lasts. This is supported by the documentation for SIA 2040 (Pfäffli & Preisig, 2017, p. 31), which emphasizes that a significant part of the energy used, and the greenhouse gas emissions are in the supporting structure, namely the raw construction. This part is usually not renewed during a renovation and its greenhouse gas emissions were accounted for in the first life of the building. The greenhouse gas emission balance for a renovated building (second life) is therefore much better. According to the efficiency path, new buildings can only achieve a 25% reduction in emissions compared to current levels. For retrofits, this can be more than 50% (Pfäffli & Preisig, 2017, p. 16). A replacement building is only worthwhile if the heat demand of the existing building cannot be reduced (no changes to building envelope possible or poor building envelope factor), or a new building allows a larger building volume, larger usable areas, and a more compact design (Pfäffli & Preisig, 2017, p. 31).

5.1.2 Effects of the building design

In principle, a small ratio of the total building envelope to the energy reference area means that the target values can be better achieved. This means that large and compact buildings achieve the guideline values better than small buildings with a large building envelope. This has to do with the heat losses via the building envelope (Pfäffli & Preisig, 2017, p. 21). Even more, small buildings also rate worse in terms of their embodied impact per energy reference area compared to large buildings. The construction method can hardly compensate for an unfavourable building size and compactness. On the other hand, however, it can be said that large and compact buildings could still be planned and constructed in a solid construction or with an elaborate facade without endangering the SIA efficiency path target values. The compactness, the size and the less complex building technology can compensate for the massive construction in such cases (Pfäffli & Preisig, 2017, p. 28). To conclude, small buildings come with more difficulties in achieving the desired values of the SIA efficiency path compared to large buildings (Pfäffli & Preisig, 2017, p. 27).

As shown in this thesis, the negative environmental impact of a building results mainly from the large use of reinforced concrete. Additionally, the MFH Lisa has the greatest environmental impact on the earth level due to the large amount of reinforced concrete and the extensive and intensive waterproofing and insulation work on the exterior of that level. Underground structures should therefore be located under the building, if possible, in order to avoid costly roof surfaces under terrain (Pfäffli & Preisig, 2017, p. 29).

5.1.3 Reduction of high impact building materials

The literature increasingly shows that mainly solid wood constructions can replace reinforced concrete in certain areas of a building. Increasingly beech or beech tree is heard in this manner. The documentation for SIA 2040 also shows, with several examples, that solid wood constructions can be used for walls (Pfäffli & Preisig, 2017, p. 37). Certain parts of the building, such as parts of the basement or the staircase, will probably continue to be made of some form of concrete. This is due to structural, water and fire protection reasons (Pfäffli & Preisig, 2017, p. 37). However, Wooden buildings are by no means just wishful thinking, as there are already several examples today and the number is growing. In Rotkreuz, Zug, Switzerland, there is the Suurstoffi 22, a high-rise building constructed of wood. Concrete is only used in the two cores and as a pressure area for the wood-concrete composite structures of the floor/ceiling plates (hybrid ceiling plate) as shown in Figure 17.

Figure 17: *Hybrid ceiling slab/plate* (ERNE AG Holzbau, 2017)

The concrete is used for fire protection, sound insulation, and as a heat and cold storage that is activated by a ventilation system within the hybrid ceiling plates (ERNE AG Holzbau, 2017). By planning with Building Information Modeling (BIM), all parties were included and worked with the same plans to reduce error rates and coordination problems. Furthermore, this planning enabled the prefabrication of the wood components with robots (digital fabrication). These factors mean that such buildings are superior to solid concrete buildings in terms of time.

The economic efficiency is therefore also justified (ERNE AG Holzbau, 2017). A high-rise building made of wood is also being planned in Zug, Zug, Switzerland. As with the Suurstoffi 22, wood-concrete composite ceilings will be used. The concrete layer in this hybrid floor construction will be only 80-90 mm thick (von-Büren, 2019). For both examples, mostly beech wood was or will be used.

Interestingly, sustainable changes in concrete construction are also possible. Fiber and textile-reinforced concrete is often mentioned in this context. Fibers or entire meshes can be inserted into the concrete in addition to the reinforcement. This increases the tensile strength and load-bearing capacity of concrete. Consequently, the amount of concrete can be reduced, which reduces the environmental impact and the weight. But the corrosion-free textile reinforcement also means that less concrete cover is required. Interestingly, for medium loads, steel reinforcement can now be dispensed with altogether (Grimm, 2022). Recently, interesting research has been carried out on carbon concrete with carbon meshes as reinforcement. Material sourcing and recycling of carbon concrete is only in its infancy. But there are already sustainable approaches to recycling by separating the concrete matrix from the carbon (Kranich, 2017). Even more, there are approaches to gaining Carbon from the carbon dioxide in the air or from wood (Holfelder, 2022). Production can also be made more environmentally friendly by, for example, adding fly ash from coal combustion or granulated blast furnace slag from steel production. Both reduce the need for burnt limestone and clay. This reduces energy requirements and GHG emissions (Schröder, 2022). Another interesting research project comes from Empa, in collaboration with Holcim and other partners. This group developed a lightweight concrete floor construction that can save 70 percent of material Figure 18.

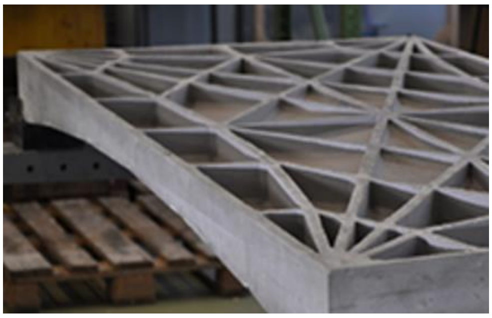

Figure 18: *Lightweight concrete plate* (Empa, n. d.)

5.2 Reduction of operational environmental impact

For the operational phase of a building, the literature shows that it is economically possible today to create net-zero or nearly-zero energy buildings. For this, the energy efficiency for all building energy uses must be maximized. With energy efficient appliances, it is possible to reduce the operational electricity demand by up to 55% compared to today's average values. The remaining loads must be covered with locally produced renewable energy sources (Ürge-Vorsatz et al., 2020) or with a supply contract for electricity with an ecological added value (Pfäffli & Preisig, 2017, p. 29).

5.2.1 Environmentally friendly operation concepts

Considering efficiency, the demand for heat for hot water heating can be reduced by constructing short distribution lines in new buildings and in retrofits if possible. This is because 40-50% of the energy demand for hot water accounts to storage and distribution losses. These losses can be reduced to 20-30% with these measures. This already allows for significant savings (Pfäffli & Preisig, 2017, p. 29). The self-sufficient (autark) house in Brütten shows that this is feasible and already done in practice (Umwelt Arena Spreitenbach, n. d.). An autark building has no grid connection and supplies itself with energy at all times. This requires a high level of technical effort for renewable electricity generation and hydrogen production and storage. The GHG emissions are no lower than for a building with PV on the roof, a heat pump and efficient insulation. However, the total annual costs are at least 80% higher.

Nonetheless, buildings that incorporate photovoltaic and a heat pump can operate as a plus energy building that has an ecological energy neutral sourcing for heat and electricity (Vaillant, 2022). Such concepts are therefore not justifiable on environmental and economic terms (Mahler et al., 2019). So called passive building designs, which use at most 15 kWh/m2 for space heating, will be crucial to manage interior temperature in hot climates (Dahlstrøm, 2011). With plus-energy houses and their consistent local power generation, the operational GHG emissions can be compensated with the production of renewable energies. Consequently, only the emissions of the construction remain in the balance sheet. By maintaining the raw construction during renovation, the balance of a building can be further reduced after renovation (Mahler et al., 2019).

5.2.2 Heating and cooling technologies

Turning now to the heat generation, an option is woodchip or pellet heating with wood from the region. These energy carriers result in above average positive environmental results to which heat pumps achieve comparable positive results (Pfäffli & Preisig, 2017, p. 17). District heating systems are a key technology for the building sector of the future. District heating from industrial waste heat or wastewater heat together with heat pump systems can provide heat all year round. On the other hand, heat pump systems together with geothermal and ambient heat in combination with solar technology and long-term storage can provide local heat (Mahler et al., 2019). However, reducing heat demand will no longer be the sole focus of the operational phase in the future. With the warming climate, energy demand for cooling will increase (Berger, 2022, p. 19). Conveniently, cooling energy demand is aligned with solar availability, which allows the use of solar cooling technologies such as electrical chillers or thermal solar collectors with absorption chillers (Ürge-Vorsatz et al., 2020). Realizing the need for low heating and cooling energy demand, allows to recognize that an optimized building envelope is important (Ürge-Vorsatz et al., 2020). Building envelopes should be created as a thermal bridgefree airtight structure with high thermal resistance to heat transfer and a highly efficient mechanical ventilation. The heating and cooling loads can be reduced by reducing solar heat gains with shading in warm periods and enabling solar heat gains in cold periods.

5.2.3 Mechanical ventilation systems

Fundamentally, mechanical ventilation is intended for comfort and, in combination with heat recovery, reduces the heating requirement. Single ventilation systems could be a choice for the future as they come with the benefit of not needing ventilation ducts (Vaillant, 2022). However, they require electricity during operation (Pfäffli & Preisig, 2017, p. 21). If this can be supplied from local renewable production, there is little problem to that. For buildings with fossil energy carriers such systems are beneficial. However, it should be noted that their production and installation increase embodied energy, especially in case of replacements. Natural ventilation or simple exhaust air systems could be the better choice (Mahler et al., 2019). For such cases, the environmental impact, usefulness, and preferences must be weighed up for the optimal solution.

5.2.4 Financial incentives

Lack of financial support from the state or cantons to build energy efficient is no longer a strong argument. A renewable energy supply can be supported by a flexible generation and consumer infrastructure with variable electricity tariffs. Local heating systems and electric vehicle fleets with appropriate load management are suitable for this. With such pricing systems, peak loads can be reduced, renewable energy can be better utilized, and the consumer's energy costs can be lowered. However, a decarbonized energy infrastructure requires that such networks can manage a high share of renewable energies. This requires flexible power systems to balance volatile supply and demand of energy and to ensure security of supply even in a dark lull. Possible dark periods are still often an argument against large-scale heat pump supply, which is why sector coupling and energy storage are important. Especially, for single-family homes, heat pumps are among the most cost-effective supply options (Mahler et al., 2019).

5.2.5 Carbon taxes

In order to create positive incentives to reduce greenhouse gas emissions for building owners and users, CO2 pricing of energy sources could be implemented across all sectors. This would eliminate the need for complex individual subsidies for building energy standards, renovations, and heating systems. The costs would be borne by the polluters and not the consumers. As a result, users would act climate-friendly out of their own interest, because fossil fuels would become more expensive (Mahler et al., 2019).

5.2.6 Sector coupling in renewable energy systems

In the energy sector, sector coupling has recently become a dominant term. Sector coupling means the coupling of different energy sector such that available energy can be split between different energy sectors and drawn again at a later date. The storage media offered by the various sectors are of particular relevance for a flexible energy system with a high share of renewable energies. Storage technologies enable surplus energy from renewable sources to be stored instead of holding it back (curtailment of electricity). Figure 19 shows the concept of sector coupling in a simplified form. The area of power represents energy producing units such as for example photovoltaic, wind, or hydropower. Excess energy is transferred to other sectors where it can be stored.

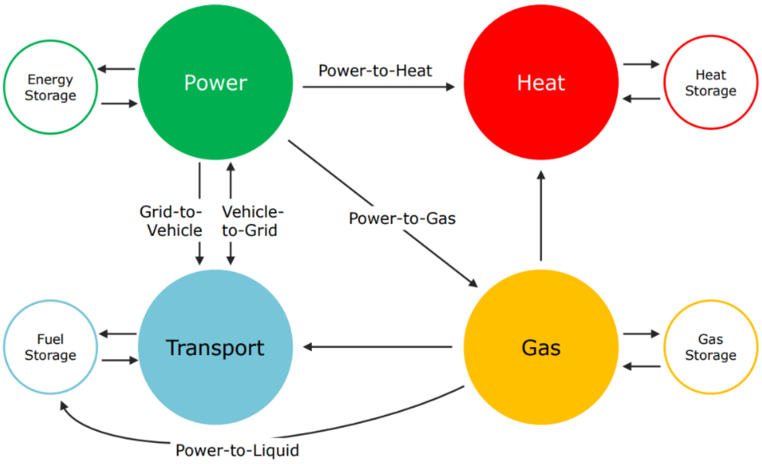

Figure 19: Sector coupling (Mühlethaler, 2022)

5.3 Possible changes to MFH Lisa

Solar on the roof would be a good option for the MFH Lisa. There is a good amount of area that could be used without any solar shading. Given that, the heat pump could be optimized for the use of the available sun hours. This would once again save electricity drawn from the grid and therefore reduce or even compensate for the environmental impact that occurred from the embodied part. (Pfäffli & Preisig, 2017, p. 21)

5.4 Main strategic findings

In general, it can be said that the embodied sector has a smaller reduction potential than the operational sector, because certain high-temperature processes in raw material extraction, production and disposal are more difficult to replace with more energy-efficient and lower-emission energy sources (Pfäffli & Preisig, 2017, p. 16). On the other hand, the reduction potential in operations clearly exceeds the target values. The additional reduction can therefore be used to compensate for the lower potential in other areas, and thus ultimately achieve net zero greenhouse gas emissions. However, this can only be achieved by consistently moving away from fossil fuels (Pfäffli & Preisig, 2017, p. 17).

6 Discussion

This study set out with the goal to understand the contributions of the embodied and the operational environmental impact of a building. For this, the MFH Lisa in Uster, Zurich was assessed in the form of a case study.

The results of this case study show that the greatest environmental impact of today's new buildings comes from gray energy. This means that the building structure with all the components is responsible for most of the environmental impact. With respect to the first research question, it was found that the total environmental impact of MFH Lisa is between 19.98 and 20.13 kg of CO_2-eq. per energy reference area and year (without and with a ventilation system with heat recovery). In terms of UBP it is between 43’607.9 and 44’015.39 UBP per energy reference area and year. The second research question sought to find the contribution of the embodied and operational part of the building. This was found to be around 73 percent for the embodied part and 27 percent for the operational part.

With the findings of the results and additional knowledge from the literature based on them, possible strategies for the building sector and adaptations of the building materials were identified in the previous chapter. As the case study on the MFH Lisa showed, reinforced concrete is clearly the dominant environmental influence for buildings in massive construction. However, reinforced concrete, as the name suggests, includes reinforcing steel as an additional building material. As the results showed, depending on the degree of reinforcement, reinforcing steel gains the upper hand over concrete in terms of environmental impact. In addition, the data from the KBOB database showed that for both materials, it is mainly the production that causes the environmental impact. In the case of reinforcing steel, this is enormously pronounced. The conclusion is that there is a large recycling potential. So-called recycled concrete is already being increasingly used today. Here, the aggregate is made of concrete granulate or mixed granulate from concrete demolition. After checking the static requirements, recycled concrete can already be mixed in such a way to fulfill load-bearing tasks on the building. As explained in the strategies section, there are also already completely new approaches to reinforcement. Fiber concrete and textile concrete with plastic reinforcements could become established in the future. Already today, fibers can be added to reinforced concrete to reduce the steel content. In certain applications, textiles are even sufficient, and the steel can be omitted. Reinforcing steel requires sufficient coverage due to corrosion. Hence, concrete can also be saved by providing less cover with the use of textiles, which do not corrode. As research conducted by Empa in collaboration with Holcim has shown, there are already approaches to designing concrete slabs according to a ribbed structure, thus saving a massive amount of material. This works based on an optimal design and control of the forces that load such a reinforced concrete slab. These findings could lead to precast concrete elements being manufactured in this way. In the case of the Lisa apartment building, some precast concrete elements have been used. These are, for example, the stairs or the balcony slabs. If 70% of material could be saved here, this would have a significantly positive influence on the embodied impact balance.

Although reinforced concrete clearly dominates the environmental impact and thus received the greatest focus in this thesis, there are other relevant materials as the A-parts of the ABC analysis showed. In particular, these are fossil resource-based materials such as plastic window frames, or various thermal insulation materials such as extruded polystyrene (XPS), polyurethane, or bitumen. As a result, windows should increasingly be made of wood and insulating materials, as in the case of the Lisa MFH, should be made of mineral materials such as rock wool. In dry areas, the frequently used expanded polystyrene can be replaced with rock wool, which can have a major positive impact on large areas such as facades. It is also debatable whether widespread use of triple glazing really makes sense. In the case of a turn towards a completely renewable energy system and thus from renewable heating technologies, possible somewhat higher heat losses via the windows with double glazing could no longer be a problem. Especially in large glass buildings, this could save an enormous amount of gray energy. These assumptions must of course be taken with caution and require further research.

With today's building standards, the building envelope is designed quite efficiently. This means that relatively little energy is required during the use phase. Despite this, how much energy a house actually requires during operation does not always coincide with the preliminary calculations to assess a building prior to the usage phase. Due to dynamic use, ventilation behavior, or room temperature, operational calculations with standard values are only close to reality to a limited extent. Nevertheless, the MFH Lisa with an assumed standard use has an annual heating demand of about 45.1 kWh related to the energy reference area (ERA). By using the individual ventilation units with heat recovery, values of 37.1 kWh per ERA and year are achieved. According to a rough assessment, the Lisa MFA is thus in GEAK class B according to the building energy certificate of the cantons (GEAK). This corresponds to an energetically good residential building and is within the range of today's new building standards with regard to building envelope and building technology. This is in line with expectations, as the building has good thermal resistance values for the building envelope, which is mainly made of rock wool and polyurethane, and for the triple-glazed windows.

As several studies in the past showed, due to the use of fossil fuels in heat supply, the operational environmental impact was clearly dominant over the embodied environmental impact in the past century. This is not surprising, considering that such energy sources operate in buildings for decades. Thus, with LCA in the building sector, past studies were able to demonstrate these impacts. The comparison in Table 7 has made this clear once again. All operational outliers of the comparison have either a not completely renewable electricity mix, which is supplied to the building, or a non-renewable heating technology. With its brine-water heat pump, the MFH Lisa features a renewable heating technology, which has a good effect on the environmental balance during the operational phase. As an alternative, a wood heating system with logs or pellets, as well as a possible connection to a local or district heating network, would also have beneficial environmental properties. This is because wood is considered CO_2-neutral and, with good forest maintenance, is resource-efficient. Further, important to mention are the single room ventilators, which have only a small influence of 0.13 percent on the embodied environmental balance from its material perspective. This is a positive result given that it has been calculated that these systems will have to be replaced up to three times over the lifetime of the building, which is 60 years. It should be mentioned, however, that the installation is not included in the balance as this is not incorporated in the KBOB database. Nevertheless, the sense of comfort ventilation is often discussed in the literature resulting in a mixed view on the topic. Despite this, it has been shown that heat recovery can significantly reduce heating requirements by about 50 percent in the MFH Lisa. In addition, it can be said that with a renewable energy supply, this does not have a major impact on the environmental balance. However, in the case of a fossil energy supply, significant emissions can be saved through a lower heating requirement. On top of that, controlled ventilation systems also lead to less manual opening of windows through which heat loss is reduced and additional heat demand can be saved. Even more, the improved air quality can also prevent moisture damage. As a result, the building fabric can be preserved longer.

In general, the planned methods, which are described in detail in the methodology, could be applied to answer the research questions. However, numerous questions arose in the calculation of the heating demand. It was recognized that profound knowledge was required in the use of the MS Excel calculation tool for SIA 380/1:2016. Since the inputs to the tool are based on the specifications of the standard, the standard must be understood in detail to a large extent. This has taken some time, especially due to the previous lack of experience in working with SIA standards. The Excel tool provides some useful explanations of the required inputs. These have simplified the work with the tool. Finally, it can be said that the tool is very helpful in the calculation of the heat demand. A difficult task was the definition of the existing thermal bridges. Standardized thermal bridge catalogs provide good help, but the standard details have to be applied with certain assumptions to the actual building details. Furthermore, working with Bluebeam Revu 20, the dimensioning of the building in digital form has been convenient, but not less laborious. The biggest advantage of Bluebeam Revu 20 was the ability to capture the building's dimensions and then export them to MS Excel. The data could then be used optimally for further calculations.

The breakdown of environmental impacts into the various building sectors was complex. Initially, all building materials were declared by their type in Bluebeam Revu 20, to add them up in a simplified way for the entire building. However, a subdivision into the different building sectors would not have been possible, or only with difficulty. For this reason, the method was changed. Thus, in Bluebeam Revu 20, all building materials were declared according to material and location. Thus, after importing the data into MS Excel, the subdivision could be undertaken in Excel. Generally, Excel proved to be a good data collection and structuring tool throughout the whole thesis work.

6.1 Main findings

The main finding of the thesis is that nowadays the largest environmental impact stems from the embodied materials of a building. Furthermore, if the building envelope is constructed in an efficient manner, the operational energy demand is rather low. This leads to a comparably low operational environmental impact in case of a modern heating technology system that runs on renewable energies.

The key takeaways on how to reduce the embodied environmental impact are

- Use of recycled building material
- Simple and compact construction of the building
- Reduced use of composite materials (adhesives, mortar, etc.)
- Avoidance of elaborate underground structures
- Good deconstructability

The key takeaways on how to reduce the operational environmental impact are:

- Increased insulation (1. step for retrofits)
- Improved windows (1. step for retrofits)
- Triple glass (case dependent)
- Heating technology running on renewable energies (2. step for retrofits)
- External solar shadings
- Solar thermal (heat), photovoltaic (electricity) (3. step for retrofits)
- Natural ventilation
- Heat recovery ventilation (in case of fossil fuel heaters)
- Evaporative cooling
- Thermally active building systems
- Advanced lighting

7 Conclusions

The main goal of the study was to investigate the environmental burden of a multi-family house in terms of the embodied materials and the use phase. For this, the study was designed in the form of a case study with the multi-family house Lisa as the case study object. By means of a Life Cycle Assessment (LCA), the desired results were obtained.

One of the more significant findings of the research is the high contribution of the embodied part of the building to the environmental impact. This building stock, consisting of the materials and appliances, is responsible for around 73 percent of the total impact. Hence, the operational phase contributes around 27 percent to the total impact when considering a standard Swiss consumer electricity mix. These findings indicate that the construction sector has improved in terms of the operational efficiency of residential buildings. As the results show, new constructions according to today's building standards can lead to a significantly reduced heat demand during the use phase. In combination with renewable energy carriers for the heat and electricity generation, the operational part of a building is showing less concerns regarding the environment. Generally, it is observable in practice and the literature that more focus is put on the operational phase. However, current data highlights the importance of necessary changes in terms of material usage and construction types. The research has shown that the commonly applied massive construction type with reinforced concrete pollutes the environment quite strongly. These findings suggest that alternative building materials for reinforced concrete must be found. In general, it seems like the problem is being recognized and new building structures are assessed. As an example, wooden prefabricated elements are on the rise and are increasingly used for building structures due to their ease of sourcing, fabrication, and CO2-neutrality.

8 Recommendations

Taken altogether, the study recommends analysing buildings for their potential environmental impact as early as the planning stage to be able to make possible improvements. Furthermore, awareness of the environmental impact of building materials should be raised in the industry to drive innovation. It is recommended that future buildings are analyzed for their potential to use more sustainable materials. This requires the interaction of clients, architects, and construction companies. It is assumed that reinforced concrete is used today at many building points where it would also be possible to use other more sustainable products, or at least to reduce the amount of concrete. Reinforced concrete is the most influential material, but there are other materials that should be treated with importance. LCA could very well be used in construction design offices to assess a building project according to its environmental impact already before construction. This would help identify which materials could be replaced with alternative, more sustainable materials. Furthermore, it is recommended to facilitate access to information on environmental data. Tools such as the calculation program for SIA 380/1:2016 or the KBOB database are freely available, which makes such analyses accessible to a wider audience. However, background data and standards are often not publicly available or free of charge.

8.1 Future research

Future research could analyse the MFH Lisa in another case study with possible alternative construction details. If data is available, an analysis of the effects of alternative concrete types on the result could be of interest. Furthermore, a technological and economic analysis of the solar potential of the building could lead to interesting conclusions in terms of its cost and benefit. It is also recommended to find alternative materials to the most influential materials discussed in this thesis.

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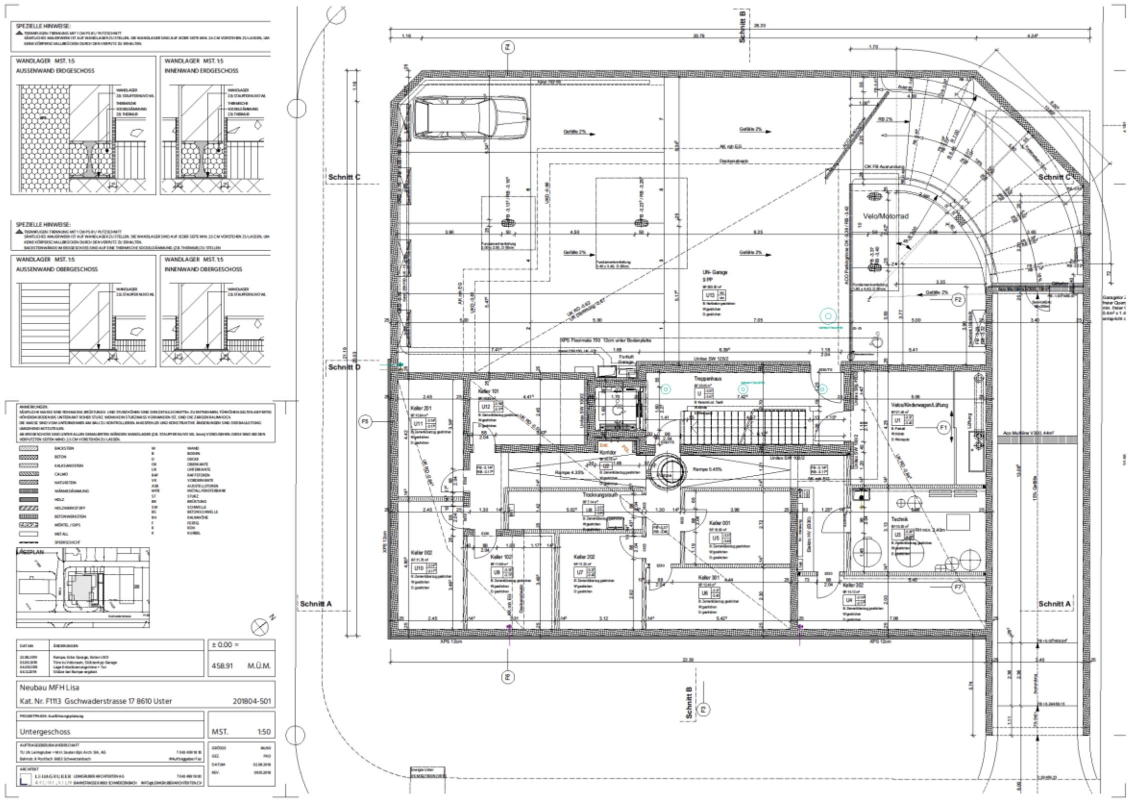
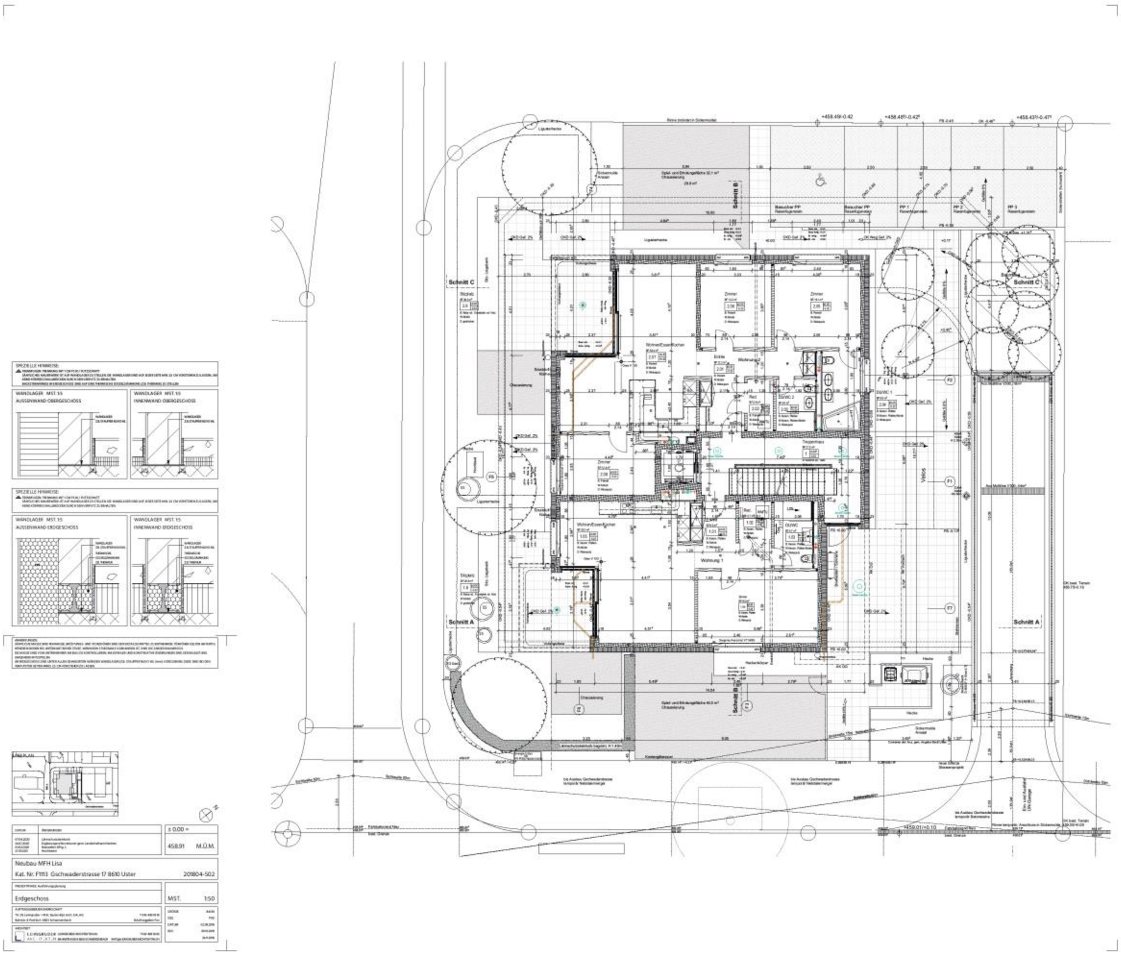
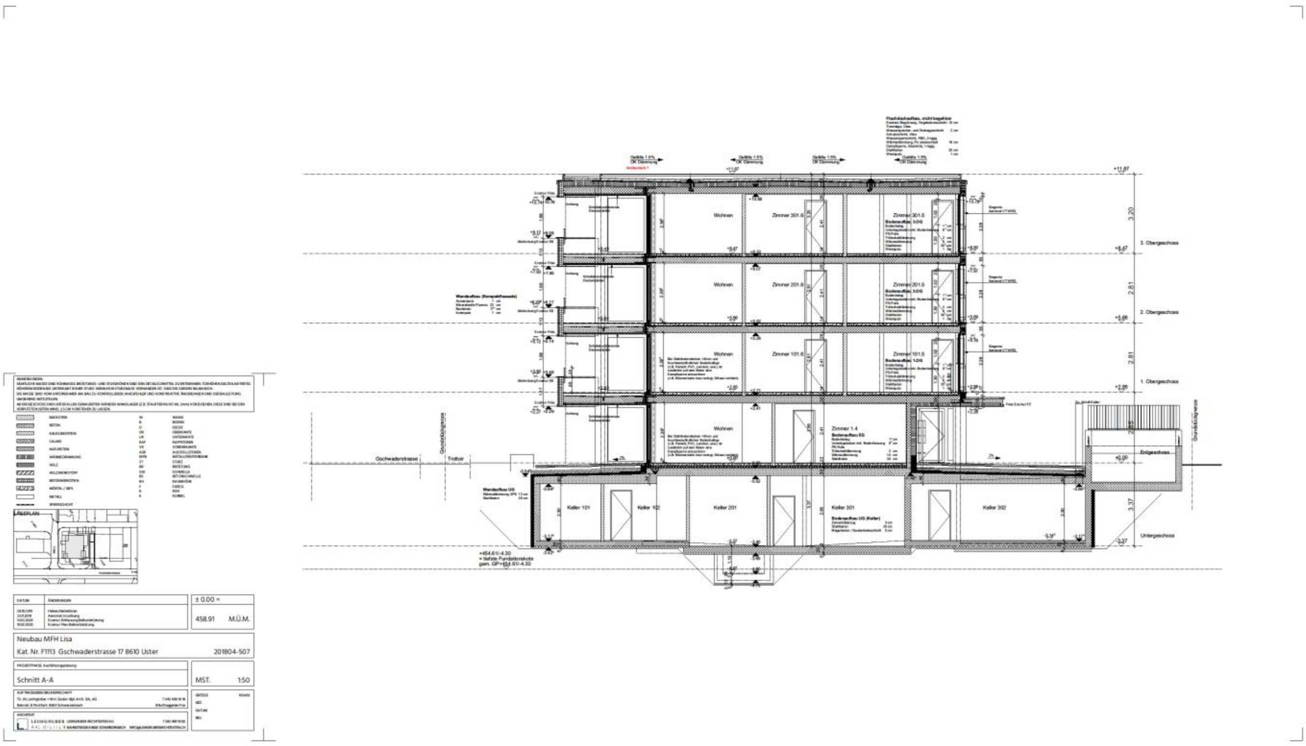
Appendices

Appendix A: Technical building plans of MFH Lisa



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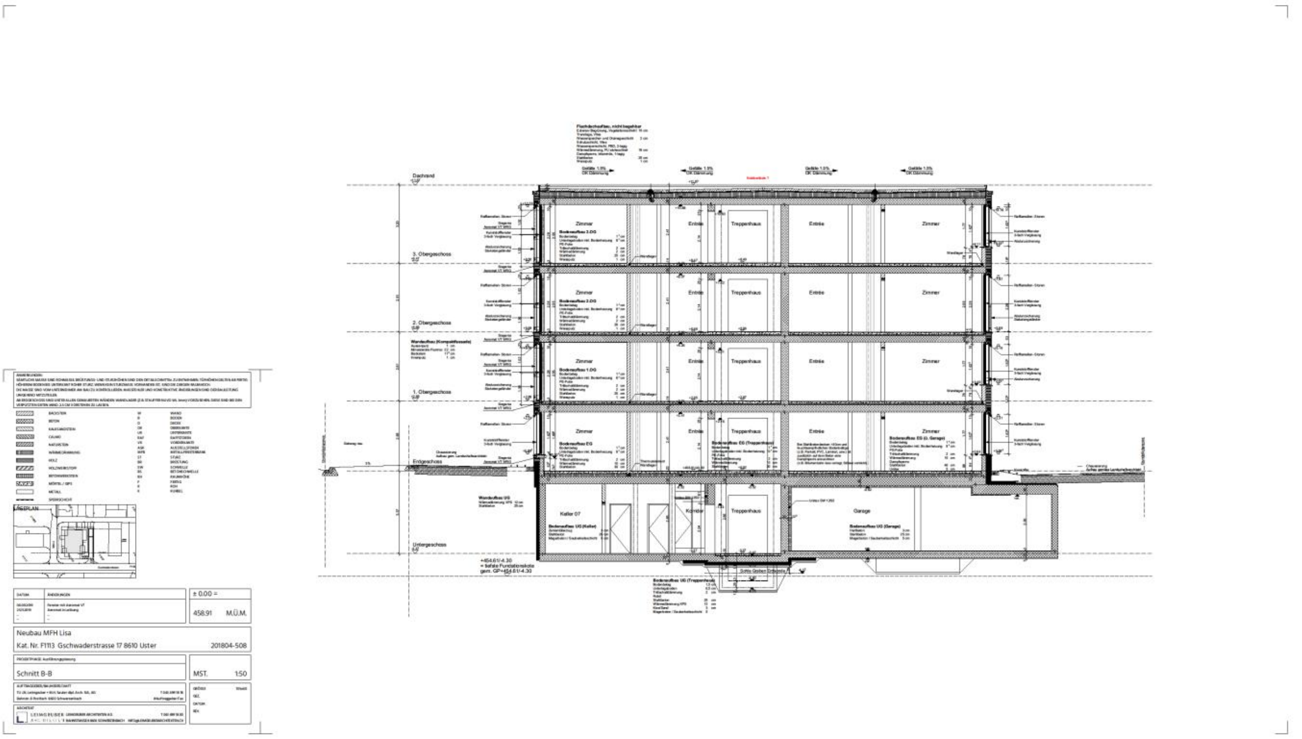
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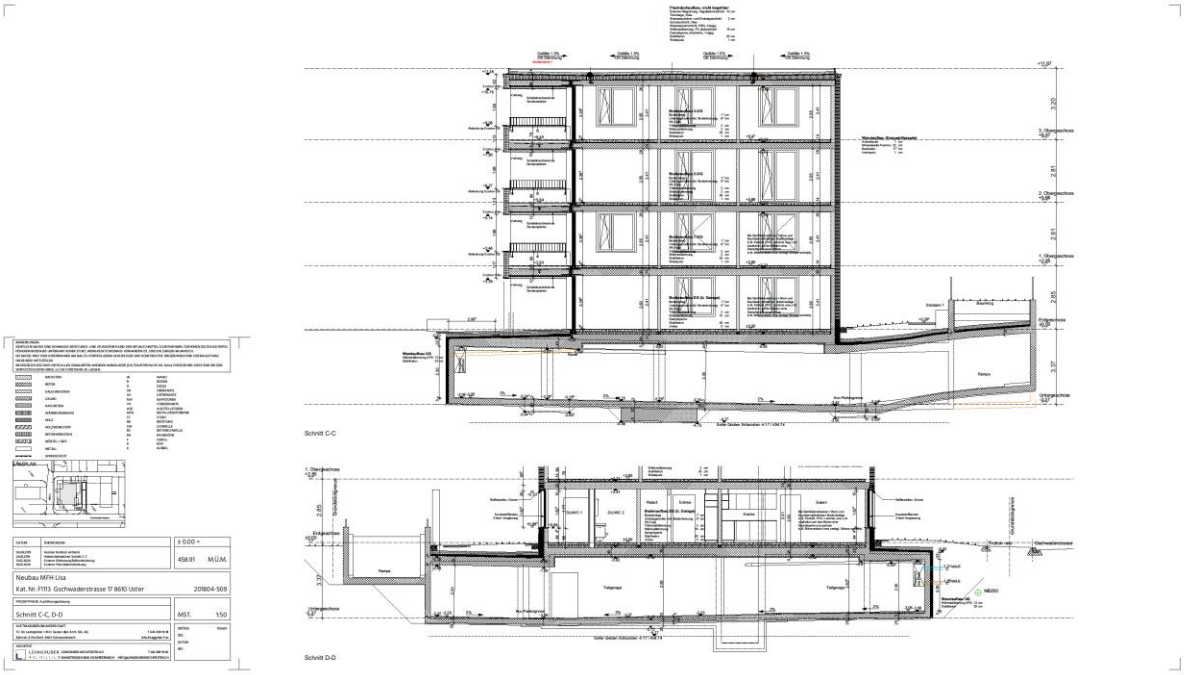
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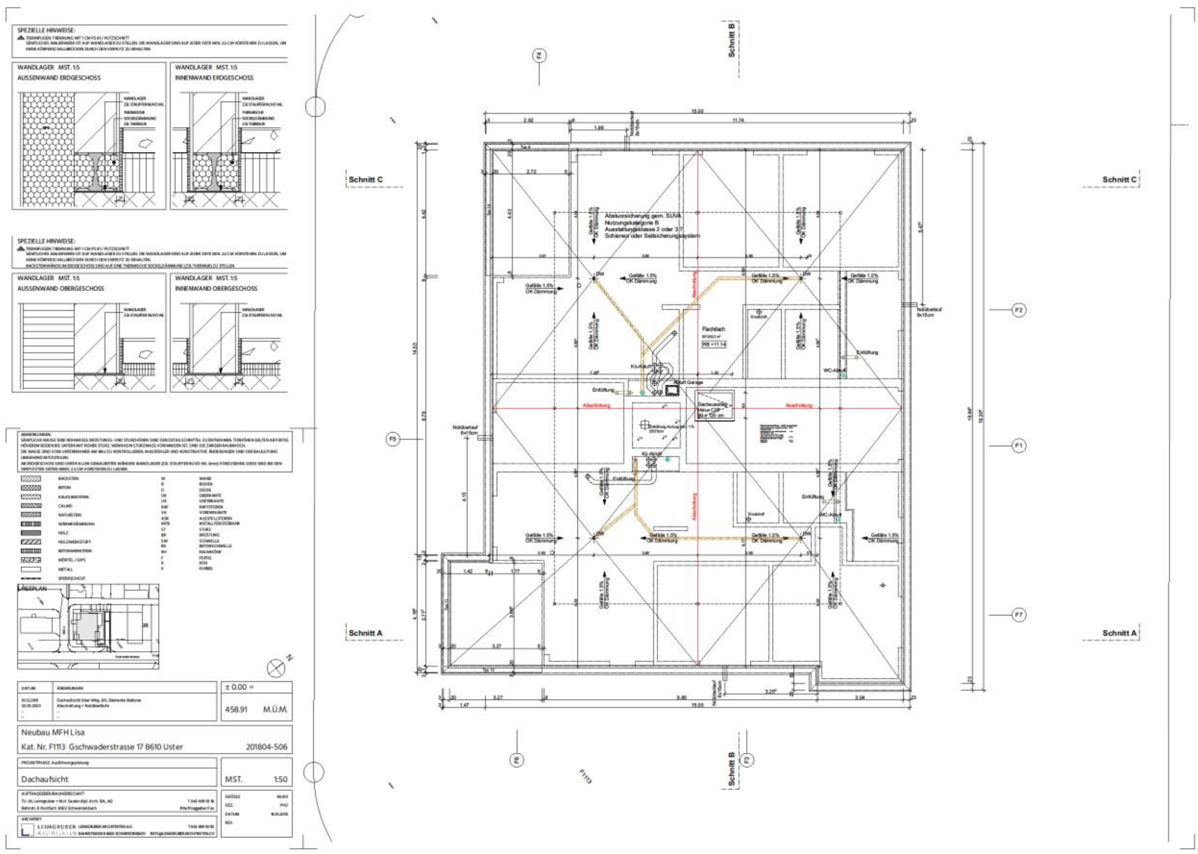
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