Evaluating Environmental Impacts: Embodied Carbon Assessment of Ventilation, Electrical, and Plumbing Systems in Swedish School Architecture

A case study from Hedda Gymnasium in Lund, Sweden

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Master thesis in Energy-efficient and Environmental Buildings
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Lund University

Lund University, with eight faculties and several research centers and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 112 000 inhabitants. Several departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 6,000 employees and 47,000 students attending 280 degree programs and 2 300 subject courses offered by 63 departments.

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The degree project is the final part of the master's program leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

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Keywords: Embodied carbon, life cycle assessment, building service systems, MEP, HVAC, carbon footprint, climate change

Publication year: 2024

Abstract

There is a rising demand for decarbonizing the building sector since it significantly contributes to global carbon emissions. With a focus on the mechanical, electrical, and plumbing systems specifically, this master's thesis explores the embodied carbon within these building service systems. Utilizing established life cycle assessment methodologies, the case study thoroughly examines the embodied carbon emissions of the ventilation, electrical, and plumbing systems for stages A1-A3, which include the production stages: Raw material supply, transport, and manufacturing of the products used within the case building.

To determine the individual MEP (mechanical, electrical, and plumbing) components that contribute to the overall embodied carbon footprint of the building, the thesis thoroughly assesses each component of these systems to accurately measure the emissions. The study's methodology makes use of a broad range of information-gathering techniques, including the use of environmental product declarations (EPDs), generic data sources, and building product declarations (BPDs). By doing this analysis, the study also highlights the barriers and difficulties caused by uncertainties in the availability of environmental data and possible resolutions for these obstacles.

Among mechanical, electrical, and plumbing installations in buildings, ventilation, particularly duct systems and AHUs (air handling units), have the highest climate impact compared to other parts of the systems. Through hotspot analysis, it became possible to identify specific components within ventilation, such as the duct system, with the highest climate impacts. The study then proposed the utilization of recycled steel material for this section, leading to a reduction of the ventilation part's carbon footprint by 30%.

Acknowledgments

We would like to express our gratitude to our examiner, Åsa Wahlström, and supervisor, Catarina Warfvinge, from the Lund University Faculty of Engineering, for their insightful advice and guidance during this master's thesis. Their assistance has been crucial for establishing the course of our study and helping us overcome obstacles along the way.

Additionally, would like to give a special heartfelt thanks to Daniel Barnekow of Assemblin for his generous contributions, insightful advice, and continuous support throughout this project. His knowledge and commitment have made this master's thesis far superior.

Furthermore, we want to express our gratitude to all the professors and students in the master’s program of Energy Efficient and Environmental Building Design for their support, inspiration, and companionship over these two incredibly fulfilling years. This adventure has been wonderful and unforgettable because of you.

Lastly, we would like to express our sincere appreciation to our friends and family, whose constant support and inspiration have served as a pillar of strength for us during this journey.

Helsingborg 2024

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Abbreviations

CO_2	Carbon Dioxide
CO_2 ***eq.***	Carbon Dioxide Equivalent
GWP	Global Warming Potential
GHG	Greenhouse Gas
SBTi	Science-Based Target Initiative
LCA	Life Cycle Assessment
EPD	Environmental Product Declaration
BPD	Building Product Declaration
PCR	Product Category Rules
IPCC	Intergovernmental Panel on Climate Change
BoM	Bill of Materials
MEP	Mechanical, Electrical, and Plumbing

Definitions

Global-warming potential	Is a term used to describe the relative potency, molecule for molecule, of a greenhouse gas, taking account of how long it remains active in the atmosphere.
Life cycle assessment	Methodology for assessing the environmental impact of a product over the entire period of its life cycle.
Scenario	In LCA a scenario is defined as a description of a possible future situation relevant to specific LCA applications. Based on assumptions about the future and shows development from present to future
A1-A3	Life cycle stages A1-A3 is an assessment of a partial product life cycle from resource extraction (cradle) to the factory gate.
System boundary	Set of criteria specifying which unit processes are part of a product system
Life cycle phase	One distinct chapter in the life of a product, e.g. manufacturing
Functional unit	Quantified performance of a product system for use as a reference unit
Data quality	Characteristics of data that relate to their ability to satisfy stated requirements
Hotspot analysis	The process of identifying regions or elements of a system that have a noticeably greater influence or concentration than others
A_{temp}	The area of every heated floor within a building envelope
BTA	Gross floor area

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1. Introduction

Sustainable development has been one of the most talked-about topics in our society for the past several decades. On one hand, environmental problems must be addressed immediately in order to protect the environment for present and future generations. On the other hand, it is projected that population growth will pick up speed in the upcoming years. According to the United Nations (United Nations, 2018), there will be a 2.8 billion rise in the world's population between 2011 and 2050. With this, social and economic activities are expected to become increasingly competitive. Population growth increases the demand for resources such as food, energy, water, and materials, which raises the question of waste output and CO2 emissions. Currently, more than half of the world's population lives in cities, and as more people move from rural to urban areas, this trend can be expected to continue (Kumar & Durai, 2019).

Although buildings are essential to a country's socio-economic growth, they also have a significant influence on the environment. Improving the population's quality of life without sacrificing Earth's overall quality of life is very important. In order to achieve this balance and pursue sustainable development within the building sector, sustainable construction is a must. Globally policies that support sustainability are being put into place to be able to meet these goals. A life cycle approach is being integrated with new standards and methodologies that have recently surfaced, in order to evaluate the environmental impact of buildings. According to the United Nations Environment Program (UNEP, 2017), by applying these methodologies, the overall building energy usage may decrease significantly from around 80 down to 30 percent.

Achieving a balance between lowering the embodied carbon and reducing the operating energy emissions is crucial to be able to minimize a building's carbon footprint during its lifetime. While embodied carbon is released during manufacturing, construction, and restoration and cannot be removed thereafter, operational carbon emissions happen while the building is in use. It is anticipated that embodied carbon will account for about half of the emissions in the built environment by 2035 (Eleuterio, 2023), due to the cleaner energy sources and more efficient technologies for operational usage. However, as environmental consciousness grows on a worldwide scale and legal framework force real estate companies to reduce their operating emissions, buildings emissions are expected to decline. Yet, carrying out renovations are essential to achieve this decrease, which again, raises the embodied carbon. Achieving a balanced carbon footprint during a buildings life cycle demands careful consideration of these aspects (Eleuterio, 2023).

Based on the literature review, it becomes clear that the building industry's pursuit of sustainable growth is a complex undertaking that needs both teamwork and innovation. We face more pressing difficulties from urbanization, population growth and environmental deterioration, making it more important than ever to strike a balance between social progress and ecological integrity. Approaches to sustainable building design provides a pathway to this balance since they are supported by strict regulations and progressive laws. We may strive towards reducing the carbon footprint of our built environment by adopting a holistic approach that considers the full life cycle of buildings and gives priority to the reduction of both embodied- and operational carbon emissions. We need to continue to work towards creating a future which buildings not only promote human health but also enhance the resilience and health of the earth.

The purpose of this research is to assess the embodied carbon of an educational facility, which includes the energy used int the manufacturing process of the components for the main building service systems. Examining these elements closely is crucial in order to identify the main sources of embodied carbon and focus areas throughout buildings lifespan to and suggest substitute materials that can help create a more sustainable built environment. Assemblin, the organization that gave us this thesis subject, has a special interest in the study's findings as they want to be well-positioned to take advantage of any future regulations from the Swedish National Board of Housing, Building and Planning (Boverket). They are actively getting ready to measure the embodied carbon of buildings and associated systems as part of their commitment to assuring compliance and early response to the new upcoming regulatory frameworks.

1.1. Climate change

The Intergovernmental Panel on Climate Change (IPCC) reports that, primarily caused by human activity, the average global temperature on Earth has increased by around 1 degree Celsius since the beginning of the industrial age. In addition, another 1,5 degrees Celsius is predicted to rise if the current circumstances are continuing (Ipcc, 2022). The emissions of greenhouse gases (GHG) are acknowledged as the biggest contributor to climate change. A greenhouse gas declining curve has already been put in place to lower the impacts and to limit the temperature increase in global temperatures to below 2 degrees Celsius by 2023 (McKinsery&Company, 2010).

According to studies conducted in 2018, the building and service sector in Sweden accounts for approximately 40% (Energimyndigheten, 2022) of the energy use and causes 22 % (Boverket, 2024) of the greenhouse gas emissions from an LCA perspective. To mitigate this, the Swedish government adopted a climate policy in 2017 that requires the country to have a net zero GHG emissions by 2045 (Ministry of the Environment and Energy, 2017). Since the building and service sector is so large, it plays a crucial role in achieving these goals. To be able to lower the life cycle GHG emissions, it's necessary to carefully design these systems to use as little energy as possible as well as look into the cradle-to-gate manufacturing processes. In order for everyone to do that, a recent initiative called "climate declaration of buildings" was created in Sweden, which aims to increase awareness of these issues and minimize the impact the buildings have on the climate. This initiative came into use in January 2022 and requires new constructions to declare their carbon footprint (Boverket, 2023a).

These regulations that came into effect 2022 marks an initial first step towards regulating the carbon footprint of construction. However, these regulations does not take into account any specific benchmarks for the building service systems, only made it mandatory to declare the carbon footprint by an annual climate declaration. Currently, the Swedish National Board of Housing, Building and Planning have produced a plan to further develop the regulations regarding the climate declarations on buildings (Boverket, 2020). This plan includes a proposition to extend the scope of the climate declaration to cover the entire life cycle of a building and its components as well as regulations about benchmarking of the carbon footprint. These developments highlight how the environmental regulations are changing within the industry with emphasis on the need for more research and analysis, like the one done in this paper, in order to support sustainable industry efforts and to address climate change properly.

1.2. Supporting emissions targets

The Sustainable Buildings and Climate Initiative by the United Nations Environment Programme (UNEP) acknowledges and emphasizes the role that the built environment plays in how humans use natural resources. The UNEP estimates that the building and construction industry are responsible for more than 30% of greenhouse gas emissions and 40% of global energy use (United Nations Environment Programme, 2016).

In response to this issue, developed countries were required by law to lower their greenhouse gas emissions. These laws came into effect during the Kyoto Protocol's second implementation term, which started in 2008 (UN, 2018). According to the Climate Act of 2008, this law requires the net annual GHG emissions by 2050 to be at a minimum 80% lower than 1990 base levels (*Climate Change Act 2008*, 2008).

In addition to this, several Commission proposals intended to bring the EU's energy, transportation, taxation, and climate policies into line with an aggressive approach were adopted in 2021, marking a major step forward in the European Union's response to climate change. By reducing net greenhouse gas emissions from 1990 levels by at least 55% by 2030, the EU will then be on pace to meet its climate goals, according to these suggestions (Europe's 2030 Climate Ambition, 2020)

Alongside these initiatives, the 2021-founded MEP (mechanical, electrical, and plumbing) target became a significant project in the construction industry, uniting stakeholders to accomplish net-zero carbon emissions by 2040. This complex initiative focuses on the carbon footprint that comes with construction materials in addition to the daily energy use for heating and cooling. The MEP2040 target lays the path for a more sustainable future for our built environment by encouraging collaboration between the design and construction industries, creating low-carbon materials, and promoting energy-efficient building technologies (*MEP and Embodied Carbon*, 2021)

1.3. Current policy on embodied carbon emissions

Sweden, as a cosigner to the 2015 Paris Agreement together with the European Union, has made a commitment to the ambitious goal of becoming carbon neutral by 2050. In order to meet these climate targets and fulfill its obligations, Sweden as well as every other European country needs to push for significant carbon reduction across the whole industry, giving more emphasis on the building sector, since it accounts for roughly one-third of all emissions in Europe (United Nations, 2015).

Elaborating on these efforts, the Swedish National Board of Housing, Building and Planning (Boverket) was given a government commission in February 2022, to create recommendations for speeding up the adoption of climate benchmarks and further broadening the use of climate declarations for buildings. These efforts aim to set a maximum climate impact benchmark created and regulated by legislation relevant to climate declarations for modules A1-A5 and will be quantified in Kg CO2 equivalent per square meter of building floor area (Boverket, 2023a).

So far, the primary focus has been set on increasing energy efficiency during the building's operational phase, with the aim of reducing carbon emissions in the building sector. Although these initiatives might be essential to the reduction, not all emissions connected to the building sector are included in them. That's why it's important to broaden our perspective and efforts by including building new buildings and remodeling old ones with environmentally friendly and low-carbon materials and techniques.

1.4. Research questions

The following research questions are addressed in this study, with a focus on conducting an embodied carbon assessment of the ventilation, electrical, and plumbing systems at Hedda Gymnasium in Lund:

1. Considering the materials and essential components, what is the embodied carbon footprint per square meter (m^2) associated with the ventilation, electrical, and plumbing systems in the Hedda Gymnasium building in Lund?
2. Does the carbon footprint of the Ventilation, electrical, and plumbing systems at Hedda Gymnasium fall within acceptable ranges when compared to similar studies and Boverkets benchmarks?
3. How can the materials of ventilation, electrical, and plumbing systems be improved/replaced to reduce the embodied carbon footprint?
4. Is there sufficient environmental data available to enable the conduct of an embodied carbon assessment for ventilation, electrical, and plumbing systems?

1.5. Goal

This research aims to evaluate the embodied carbon emissions linked to the building service systems of Hedda, a gymnasium in Lund. The facility's ventilation, electrical, and plumbing systems are going to get particular attention. The main goal is to calculate the amount of CO2 emissions that are produced during the material extraction, production, and transportation phases of the life cycle, also called A1 through A3. The bill of materials (BoM) list was provided by Assemblin, the company responsible for the building service systems, in order to facilitate this assessment.

By comparing the results with findings from related research, validation will be carried out to assess the accuracy of the study. The system group with the highest global warming potential will be determined by doing a hot spot analysis, a method to identify parts with the highest climate impact (see chapter 5 for more details and explanations). The goal is to calculate the total amount of kg CO2 equivalent emissions that can be reduced when materials of the system group are replaced with alternatives with less embodied carbon.

1.6. Scope

- Perform a climate calculation of the Hedda gymnasium's ventilation, electrical and plumbing systems, with an emphasis on calculating the embodied carbon footprint connected to each system.
- In order to offer a comprehensive knowledge of the climate impact, the evaluation will include phases A1 to A3 of the life cycle.
- To ensure accuracy and dependability in the evaluation process, embodied carbon data will be analyzed and calculated using environmental product declarations and generic data, and the results will be validated by being compared to other studies.
- Determine which building service systems components have the greatest potential for global warming and rank them according to their carbon emissions.
- Investigate other material choices and develop mitigation strategies to lessen the overall effect of embodied carbon emissions within the facility, while taking environmental performance, practicality, and availability into consideration.
- With an emphasis on fostering sustainability and resilience, the study will offer suggestions and methods for lowering the building's service systems' total embodied carbon.

1.7. Limitations

The assessment of the climate impact from life cycle phases A1 to A3, which includes material extraction, production, and transportation of the products, is this research's sole objective. Phases beyond A3 are not covered by this study. Moreover, the study only evaluates the Global Warming Potential (GWP) and excludes all other environmental impact categories.

Additionally, the report's focus is limited to one particular structure and its building service systems. The investigated products found in this building are supplied by Assemblin, and for the sake of impact calculations, it is presumed that these numbers are correct. The research's width is further limited by the availability of the data. The material composition of the products is used in the climate impact assessment when generic data or environmental product declarations (EPDs) are not available. The analysis of the building's ventilation, electrical, and plumbing systems is the exclusive topic of the report and is limited to the Hydda gymnasium in Lund. The research does not include other system components.

Moreover, it is critical to have discussions about how these restrictions may affect the study's results and suggestions. Stakeholders can better understand the dependability and practicality of the results by being open about the uncertainties and any biases present in the study. To improve and broaden the study, future research may concentrate on filling in the gaps and resolving the constraints that have been found. This might entail looking for more accurate and thorough data, investigating the full life cycle of the products, exploring different approaches or models, and taking into account other elements or variables that may have an impact on how building service systems affect the climate. We can better support sustainable decision-making and the ongoing shift to a low-carbon build environment by consistently working to increase the thoroughness and accuracy of our assessments.

2. Literature review

2.1. Embodied carbon in buildings

For a long time, the analysis of the carbon footprint of buildings has been concentrated on operational factors, focusing mainly on measures of energy efficiency e.g. increase of thermal resistance by adding insulation and considering solar gains with window-to-wall ratio (WWR) (Sturgis, 2020). However, recent studies have shown the need to expand our perspective and include embodied carbon consequences. According to a review of building life cycle evaluations conducted in 2013 by Ibn-Mohammed and colleagues, embodied carbon can account for anywhere between 2% and 80% of whole-life carbon emissions. The precise percentage depends on a number of variables, such as the purpose of the structure, its location, the choice of materials, and forecasts for future energy sources and service life (Ibn-Mohammed et al., 2013). Interestingly, certain building types—like industrial warehouses, for example—may have greater percentages, with embodied emissions accounting for as much as 90% of the total (Sturgis & Robert, 2010)

These studies emphasize the importance of maximizing the trade of between operational and embodied carbon footprints in order to create a more deep and environmentally friendly method of building design (Shadram et al., 2019). Today, very few emission policy frameworks are addressing the material choices and building techniques used in building development, even though many energy policy frameworks aim to achieve “so-called” zero carbon buildings (Ibn-Mohammed et al., 2013). This means that the procurement and processing of raw materials, transportation, upkeep, and demolition are often left out of the picture. However, a study done by (Biswas, 2014) suggests that there is a growing interest in the understanding and consideration of embodied carbon.

According to (Lockie & Berebecki, 2012), the reason why embodied carbon emissions in buildings and manufacturing processes have received less attention stems from the relative effect of embodied carbon tends to grow when operational carbon drops. However, most industry targets and standards pertaining to embodied carbon tend to concentrate on architectural building materials, frequently overlooking the noteworthy influence of ventilation, electrical, and heating & sanitation systems. Nonetheless, new research has started to highlight the significant embodied carbon footprint connected to MEP systems. About 15% of the embodied carbon in a new office building comes from MEP services, according to LETI (LETI, 2020).

In Sweden as well as throughout Europe and the world, there has been a notable increase in recent years in the efforts to mitigate the climatic impact caused by new building development. In Sweden, in particular, the government and the Swedish National Board of Housing, Building, and Planning are leading the development of a new legislative framework that requires climate declarations for new structures (Boverket, 2023a; Malmqvist et al., 2023).

Multiple projects within the building and civil engineering sector are undertaken in parallel with official efforts. For example, the industry is committed to becoming fossil free, as stated in the "Fossil-free Sweden" plan (Lenberg et al., 2024), in addition to several municipal and regional initiatives. Furthermore, several developers are actively investigating climate standards for new building projects that are based on performance. One notable effort to evaluate creative methods for incorporating climate factors without sacrificing financial sustainability is the "Climate Requirements at Reasonable Cost" project (Thrysin et al., 2023).

Nevertheless, as Boverket states, the existing regulatory framework in Sweden does not require MEP systems to be included in the mandatory climate impact calculation under the climate declaration law (Boverket, 2023a). This evaluation currently only covers the building exterior, inner walls, and load-bearing structure. But with Sweden establishing new national goals to lower greenhouse gas (GHG) emissions from the construction industry, the emphasis is moving from primarily looking at the structural framework and foundations to looking at more components of the building infrastructure (Stigemyr Hill & Borgström, 2022)

Embodied carbon, as the name suggests, is trapped in a built structure. As a result of this, when a building is complete, there is now less chance to be able to affect the portion of the building's embodied emissions. Today, embodied carbon is expected to account for an increasing number of emissions since better building operations are made possible by having a cleaner electricity mix, renewable energy sources integrated with high-end technology, and improved system efficiency process (KPMG, 2023), see Figure 1.

However, the implementation of embodied carbon legislation benchmarks has the potential to speed up the move towards sustainable development by encouraging the use of low-carbon building goods. The significance of embodied carbon emissions in product materials is also emphasized by green building rating systems these days, which encourage manufacturers to openly report the environmental data of their products and services. Using EPDs is one such reward mechanism; by earning credits, they can be used to enable higher environmental evaluation ratings. EPDs have become essential in the European construction industry since they measure the environmental impacts of building materials (Jordan & Bleischwitz, 2020), which eventually may lead to more improvements in the embodied carbon evaluation techniques.

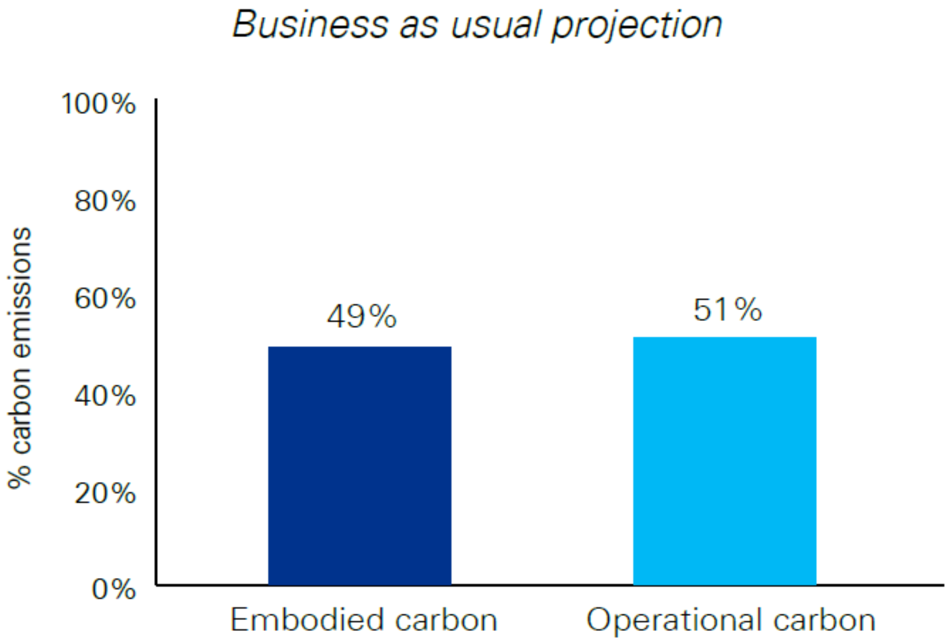

Figure 1: Total carbon emissions of global new construction, 2020-2050 (KPMG, 2023)

2.1.1. Significance of embodied energy in buildings

Energy conservation efforts were once based on the widely held belief that the energy required for HVAC systems to operate was significantly greater than the energy used in the manufacturing and installation process. These days a more advanced perspective has come to light, which acknowledges the complex dynamics of embodied energy (Dixit et al., 2010). The negative environmental impacts caused by a building's whole life cycle: from manufacturing, use, and disposal, may be similar in size to those that occur during the manufacturing phase alone (Khasreen et al., 2009). In addition to this, the building sector holds a remarkable position in the worldwide fuel consumption chain, which accounts for 20 percent of all fuel consumption through embodied energy alone (Li & Colombier, 2009). Therefore, it's important to emphasize how necessary it is to take the full life cycle into consideration when evaluating environmental sustainability.

2.2. Past research concerning the evaluation of MEP systems

Most of the current research on embodied carbon in the construction sector mainly focuses on goal setting and potential remedies. By conducting a broad literature review, with the intent to understand the nuances of embodied carbon in the building industry, several key subjects arise.

In the building sector, the total impact on the environment and the main energy consumptions of a building are significantly impacted by the life cycle of its HVAC and electrical systems (Department of Energy, 2015). Building ventilation systems has traditionally prioritized thermal comfort, but since indoor air quality (IAQ) has lately been linked to health problems, there has been a major shift in the last thirty years. Since natural ventilation can often be insufficient in densely populated areas, HVAC systems are essential (Carrer et al., 2015). Buildings are in general significant energy users, so efficient systems are essential to cut down energy usage, particularly in areas of heating, cooling, and ventilation.

Today, when evaluating HVAC systems, capital cost is taken into consideration in addition to operating cost, which aligns with the growing environmental consciousness and the requirement to mitigate external cost elements in energy-related choices (Avgelis & Papadopoulos, 2009). Costs play a significant role in market-driven economies. That's why it's important to consider both operating and capital costs when implementing HVAC systems.

Currently, improving the operational energy associated with greenhouse gas (GHG) emissions is a major scientific priority in building and energy research. However, since factors other than operational usage affect greenhouse gas emissions, the focus starts to shift more and more toward the full life cycle of buildings (Röck et al., 2020). Thanks to this, performing a life cycle assessment (LCA) is now easier than ever, because of the recent methodological improvements. More and more construction product manufacturers are creating environmental product declarations (EPDs) to provide valid LCA data for their products (Passer et al., 2015) as well as other formats that align with the global ISO 14040/14044 standards (ISO, 2006).

Life cycle assessment (LCA) is frequently used in research, especially when it comes to office and residential structures. (Röck et al., 2020) The use of life cycle assessment (LCA) for assessing and analyzing the environmental performance of buildings has due to be increased in the Nordic nations throughout the past couple of decades. (Schlanbusch et al., 2016). As a result of these assessments, it's now confirmed that the Swedish building sector represents 10-40 % of the overall energy usage, generation of solid waste, emissions of gasses that contributes to climate change, use of hazardous chemical products and human toxicological impacts. (Toller et al., 2011).

The energy usage and carbon emission of a hospitals HVAC system was evaluated in a study conducted by (García-Sanz-Calcedo et al., 2021). The study shows that the energy and carbon embodied in the building were 2.65 and 2.30 times greater than what was consumed in a single year of operation of the hospital. HVAC systems are accounting for 56% of the weight and 74% of the carbon emissions in standard MEP systems, which are making them the major contributor to a buildings carbon emission, according to (Annan, n.d.).

An additional study (Frendberg & Wiksten, 2023), carried out as part of a master's thesis at Chalmers University, examined the HVAC systems which include heating, sanitation, ventilation, and cooling systems in two different Swedish university buildings: the "Umeå Building" and the "Nya Konst." The results of their final climate effect evaluations showed that "Nya Konst" had a somewhat higher climate impact with a measure of 31 kgCO2eq./m^2, while the Umeå Building produced a measure of 30 kgCO2eq./m^2.

In commercial buildings, they have represented an impact of 15-36% of the total embodied carbon, and in residential buildings in the UK up to 25% (Keyhani et al., 2023). In another study by (Kofoworola & Gheewala, 2009), the life cycle assessment of office buildings located in Thailand revealed significant environmental impacts from the production of concrete and steel, as well as from the energy used in the creation of the components for HVAC systems. The result of this study emphasizes the need to utilize recycled materials in order to lower the building's total climate impact. Over the course of a building's life cycle, MEP (mechanical, electrical, and plumbing) systems need to be replaced frequently, which contributes to the total embodied carbon of a building.

Enebjörk (Enebjörk et al., 2022) looked at the climatic impact of different building components in two office buildings and two residential buildings in an investigation. They concentrated on sprinkler systems, elevators, air conditioning and ventilation, sanitation and heating, and electrical installations, and investigated life cycle phases A1–A3. According to the research, these installations together were responsible for up to 20% of the entire climate effect of materials in office buildings and around 8% of the total impact of materials in residential buildings.

In another study, conducted by Calderon (Calderon et al., 2022), the focus was on a preschool in Gothenburg. In order to assess the preschool's climate effect, this extensive research attempted to include all greenhouse gas (GHG) emissions related to HVAC systems across life cycle phases A1-A5, in accordance with EN 15978 requirements. However, this study was limited to products and components above 10 kg, and the ones below were neglected.

The findings showed that the school's HVAC system's estimated effect was higher than the reference values developed by Tove Malmqvist and colleagues (Malmqvist et al., 2023), indicating the need for more study to fully comprehend the variations in environmental effects across various HVAC systems.

According to research conducted by Intregral group, MEP systems account for anywhere between 15% and 49% of the total embodied carbon in commercial buildings over the calculation period of 30 years. The embodied carbon can even in some retrofit scenarios increase to 76% (CIBSE, 2021).

2.3. Barriers in building service systems embodied carbon assessments

The building industry faces practical challenges due to the complicated processes involved in determining embodied carbon. Redefining what a "zero carbon" building means is necessary to move toward objectives like "resource efficiency" and "circular economy," as outlined by the European Environment Agency (EEA, 2016). This conceptual shift requires extending carbon assessment beyond the operational stage to include embodied emissions and the full lifetime.

Additionally, effectively addressing these issues depends on having access to reliable data, strong metrics, and advanced instruments that can precisely measure embedded emissions. As such, there is an obvious need for creative research projects that strive to improve the building sector's ability to deal with carbon emissions comprehensively.

Apart from the literature analysis this study presents, it is crucial to highlight a persistent issue that has been encountered throughout many studies during the literature review; the challenge of gathering environmental data from systems or products that are used in building projects. This problem is caused by a number of things, one of which is that manufacturers' efforts to create environmental data for their products are still in the beginning phase, mostly due to that manufacturers to date are not obligated to provide EPDs (The International EPD System, n.d.).

Although the influence of building services, specifically HVAC systems, has been the subject of only a few studies, there can now be seen an increasing amount of research that aims to comprehend these services' impacts on the environment. The system's noteworthy contribution to the reduction of embodied carbon emissions is the main cause of this initiative (Hitchin, 2013). One significant obstacle that was found in the research was the limited capacity of research to be able to carry out complete assessments mainly the limitation of data available for calculating the embodied carbon. This problem was especially noticeable for HVAC components since they have a variety of raw materials (Hitchin, 2013).

For instance, Lappalainen (Lappalainen, 2021) examined the climatic effect evaluation of HVAC systems in apartment complexes. The study only looked at stages A1–A3 of the life cycle. This investigation revealed a number of significant findings, one of them being the difficulty of precisely measuring the influence of HVAC systems in apartment buildings because of the uncertainty of the data that is currently accessible.

In another study, Del Rosario and colleagues highlighted that analyzing the environmental performance of buildings and building systems through a life cycle assessment is today difficult because of the lack of environmental data. The result of this is that assessors may not be able to accurately measure the embodied carbon emissions and other environmental metrics if no reliable and country-specific data on the environmental impacts are available (Del Rosario et al., 2021).

Despite these obstacles, the industry appears to be making advancement (Fnais et al., 2022) as more producers of building materials and goods are preparing for the upcoming laws and regulations from EU domestic and foreign organizations such as the European Green Deal, European Circular Economy action plan, and EU Product Environmental Footprint to name a few. Because of this, future improvements in access to precise and consistent environmental data are anticipated as producers start to align with the new legislations and life cycle assessments start becoming the new normal, setting its benchmark in the industry. Figure 2 presents the number of built environments LCA publications over the past years.

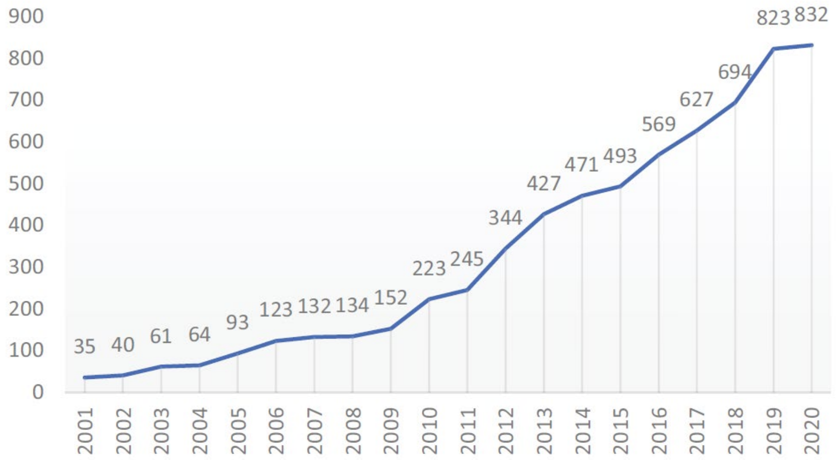

Figure 2: Number of built environment LCA publications over the past years (Fnais et al., 2022)

2.3.1. Evaluation of embodied carbon utilizing Building Information Modeling (BIM)

Building Information Modeling, or BIM has gained a lot of popularity in the recent few years as a way to simplify and create material quantity evaluations in the life cycle inventory stage of a life cycle assessment. This use of BIM has successfully demonstrated the decrease in the need for human data input, which has been highlighted in a study by (Soust-Verdaguer et al., 2017). According to (Röck et al., 2018), the main goal with using BIM is to improve the life cycle assessment performance by obtaining enough data for analytics early in the process. This method enables optimization and design considerations on-the-go. Four primary advantages are mentioned by (Shadram et al., 2016); a) minimizing the need for manual input; b) making real time evaluation easier; c) improving evaluation at later stages of the building; d) user-friendly analytical interface.

2.4. Design strategies for low embodied carbon

HVAC as an important part of the building, must provide the indoor environment with clean air, fulfilling the requirements by standards for different types of buildings and achieving maximum thermal comfort for users (Jung & Jazizadeh, 2019). The design of HVAC must find the best solution, by achieving the standards for clean air and minimizing energy use and environmental impact. There are several strategies that help to minimize the environmental impact and they incorporate holistic approaches (Ansah et al., 2022), that consider both environmental and economic factors by helping with innovative design choices, material selection, and the adoption of clean technologies (Seuntjens et al., 2024):

1. Optimal duct layout

Proposing an optimized system layout design means less material is used to build the system and at the same time the environmental impact is significantly lower (Ramon & Allacker, 2023). Ductwork is the most important part of the HVAC, according to ASHRAE there are three types of ducts, depending on their manufacturing material: metal sheeting, non-metallic, and flexible ducts (Reinforced PVC, Aluminum, several materials, etc.) (Ashrae, 2020). All these three types have advantages and disadvantages regarding energy use and environmental impact.

2. Life cycle assessment in the design phase

LCA is a comprehensive approach to reducing both operational and embodied carbon. Implementing a life cycle assessment of materials and products of the system, helps the designer to choose materials with the lowest both environmental and economic impact. Implementing LCA in the design stage helps to select the type of system that also has the best performance in terms of environmental and economic impact (Schneider-Marin & Lang, 2022). However, in the early stages of the design, it is not possible to have all the data of the new system.

3. Passive and active measures combination

Passive measures can play a significant role in reducing energy consumption and carbon emissions. Natural ventilation, thermal insulation, and other passive measures are proven to have a big effect on environmental impact reduction (Luo, 2023). A study performed by X.J. Luo an integrated passive and active retrofitting approach (By implementing passive measures: Envelope insulation, windows replacement, shading system and PV panels installation, and Active measures: New lighting system, new AC system, forced ventilation and boiler replacement) toward minimum whole-life carbon footprint in an office building as a case study (Costain House, located in Maidenhead UK), demonstrates the approach's effectiveness, showing significant reductions in costs, carbon emissions, and energy usage. Table 1 below presents the findings of the study. The proposed approach is a balanced choice between all the proposals, for example, Reference 1 (All solar panels), is an approach by providing the electricity of the building only by solar panels, Reference 2 (all wind generators), and so on. This was proposed by finding all the benefits of all references, by going through several steps: Simulation models, optimization algorithms, life cycle assessment, iterative feedback, and final step economic and environmental performance evaluation.

Table 1: Performance comparison between the proposed retrofitting strategy and conventional operating strategy-based retrofitting approach (Luo, 2023)

	Reference 1	*Reference 2*	*Reference 3*	*Reference 4*	*Proposed appr.*
	All Solar panel	All wind generator	All solar heating syst.	Combination	
Cost savings-to-investment (×106 £)	0.44	1.75	15.51	1.98	1.58
Energy reduction-to-embodied (×108 MJ)	8.48	2.27	31.17	3.94	4.20
Carbon reduction-to-embodied (×107 kg)	11.20	0.89	24.05	1.75	4.33

3. Life cycle assessment (LCA) -Theory

3.1. LCA background

Addressing environmental challenges requires the incorporation of environmental considerations regarding a range of decisions made by citizens, legislators, and governmental administrators. These decisions often concern goods and services, such as the fuels we use in our cars, generation of energy, waste management systems, and consumer goods such as e.g. construction materials. Adopting a life cycle approach that considers every stage of the process – from product manufacturing and usage to waste management and recycling, is essential in order to make well-informed environmentally friendly decisions (Cui, 2020).

Life cycle assessment (LCA), sometimes referred to as life cycle analysis, is a method for calculating the effect a product has on the environment. Through the whole life cycle, from transportation and manufacturing to the use of a product, the assessor creates a list of consumed resources and chemicals (such as greenhouse gasses, waste, and pollutants). This process is called a life cycle assessment (LCA) and is developed to evaluate the total effect on our ecosystems, human health, and decreasing supply of natural resources. Applying a LCA helps to discover severe environmental consequences in the supply chain of a product and to establish strategies to mitigate them in an early stage (Gnansounou et al., 2009).

3.2. Framework

Life cycle assessment (LCA) consists of a thorough view of a product or process's environmental impact through four key stages (ISO 14040:2006) (ISO, 2006) These stages consist of the following:

1) **Goal and scope:** Setting the goal and scope of a life cycle assessment is the first step of this process. This first essential step establishes the study's goals and objectives concerning the topic and its planned use.
2) **Life cycle inventory analysis:** To achieve the research objectives, we must acquire information by gathering relevant and comprehensive input/output data related to the research.
3) **Life cycle impact assessment:** This stage illuminates the total environmental relevance of the evaluated product system by revealing a broad awareness of the wider ecological consequences.
4) **Life cycle interpretation:** The result of the study is summarized and examined in this stage. It works as a foundation for conclusions, suggestions, and directives that can be used in any decision-making process.

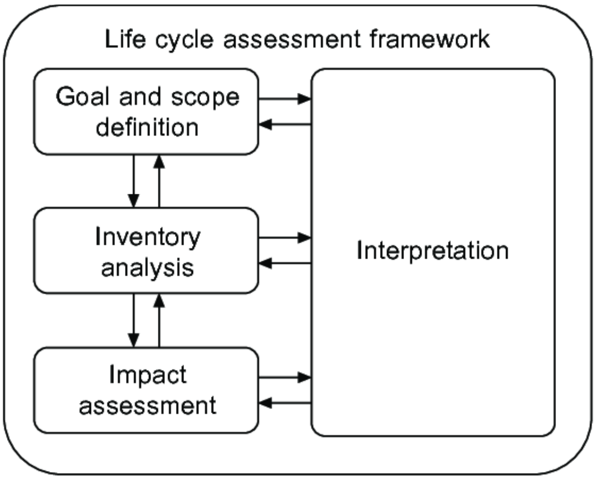

Figure 3: LCA framework (ISO, 2006)

3.3. LCA standards

With the assistance of several ISO standards, the life cycle assessment approach has gradually developed. It uses the physical sciences to estimate environmental consequences with standards that include a general framework for life cycle assessment. Even while studies of buildings have become more consistent thanks to these standards, it's important to note that the ISO LCA standards still only act as a framework, giving each research significant flexibility in the methodology used (Pomponi & Moncaster, 2018). Because of this, it may at times be difficult to compare the results of two life cycle assessment studies of the same construction, product, or service unless the methodologies used in each case study are similar. Generally speaking, LCA studies of buildings have been more challenging to achieve methodological comparability than assessments of typical, mass-produced goods. This is mainly because buildings are comparatively different, and complicated, with varied composition (Buyle et al., 2013; Cabeza et al., 2014).

It is critical to recognize that the methodological differences across different life cycle assessments may be seen as indications of uncertainties, coming from the different calculation models and scenarios used in each research (Huijbregts, 1998; Lloyd & Ries, 2007). In turn, using ISO standards as guidelines for the assessments, it helps to reduce this kind of uncertainty, but not completely remove it.

Defining objectives and scope, performing a life cycle inventory analysis, evaluating the life cycle impacts, and interpreting the findings are the four main stages of LCA research (BSI, 2006). Assessing embodied carbon is similar to assessing a subset of a life cycle assessment because it only takes carbon emissions and their global warming potential into account. Standardized functional units or their equivalent must be used for comparison in these cases, in order to maintain comparability between the findings of the studies of structures or building goods.

3.4. Life cycle energy analysis

Life cycle energy analysis is a thorough method that analyses the energy inputs used at every stage of the life cycle of a building. This stage involves three boundaries of a system, which are manufacture, usage, and demolition energy usage (Ramesh et al., 2010), see Figure 4. The manufacturing phase involves energy used throughout the production, transportation, and installation of materials and systems in renovation objects and new construction. The operational phase includes the energy utilized for the usage of the building, including keeping enjoyable indoor conditions, water management, and power systems and equipment. Lastly, the demolition process comprises the energy used at demolishing the building and its systems as well as the transportation of the disassembled materials to recycling facilities or landfills (Ramesh et al., 2010). These three energy use phases are looked at in more detail below.

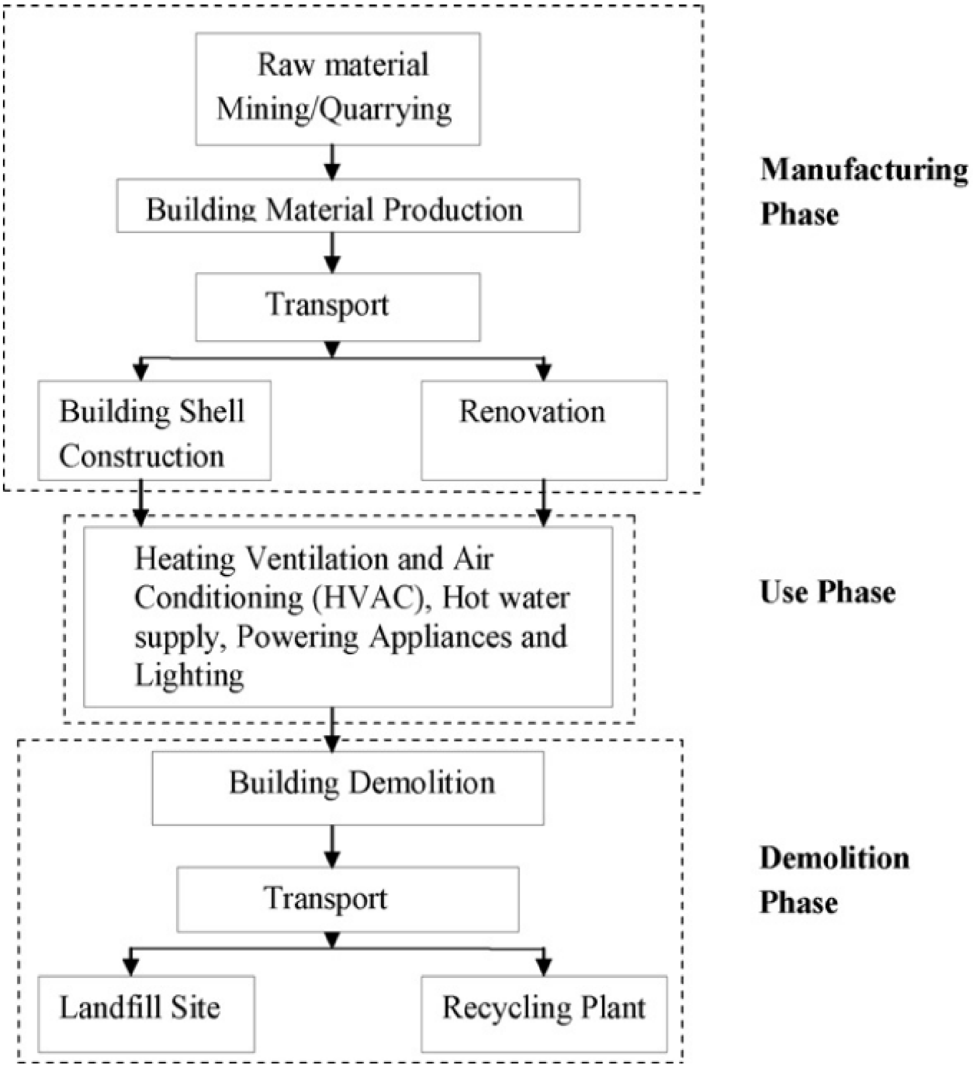

Figure 4: Manufacture, usage, and demolition energy usage (Ramesh et al., 2010)

Among the several techniques used to assess environmental impacts, life cycle assessment (LCA) is particularly well established in the field of industrial ecology. The four main steps of the ISO14040/44 standards rules of procedure articulated by (Thernström et al., 2015) are the following: Goal and Scope definition, life cycle inventory, impact assessment, and interpretation, as described in the ISO 2006a standard (ISO, 2006). According to (Reap et al., 2008), numerous studies have been conducted since life cycle assessment was first introduced to identify barriers, that limit its wider implementation in the industry. These investigations suggest difficulties at various stages of the life cycle assessment, which affects the accuracy of the methodology. (Cooper & Fava, 2006) suggests that two of the main user problems are the life cycle assessment approach and the time-consuming data collection procedure. However, the creation of techniques and tools that simplify the LCA process to overcome these barriers has in recent years been developed, with the goal of making the work process more efficient, such as the life cycle inventory process. Some of these approaches suggest addressing the environmental considerations already at the product development phase (Baumann et al., 2002).

3.5. LCA variants

A life cycle assessment can be utilized for several different lifespans, as shown in the figure below from A1 to D, in accordance with the EN standard. “Cradle to grave” refers to the complete lifecycle of a product, which starts at the stage of raw materials and ends as waste treatment, recycle or reuse. On the other hand, the “cradle to gate” phase, which this study is focused on, starts with the extraction of raw materials and ends with the final manufactured product. “Gate to gate” stage starts with waste treatment and concludes with post-production. And finally, the “cradle to cradle” stage represents the products path from the source of its fundamental components to its reuse in other processes. (*EN 15978*, 2011; ISO, 2006).

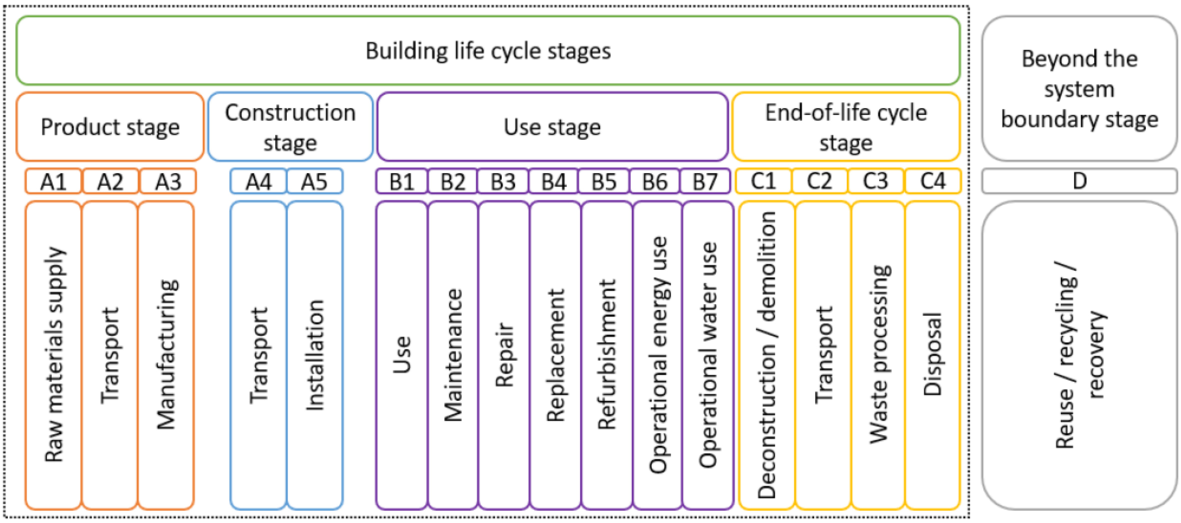

Figure 5: Building life cycle stages (EN 15978, 2018; ISO 14040, 2006)

3.6. Environmental Product Declaration (EPD)

Environmental Product Declarations (EPDs) offer important information about how the e.g. building products and components affect the environment throughout the course of their life cycle. EPDs, which are condensed versions of life cycle assessments that highlights the environmental impacts linked to a specific product. An EPD normally consists of three parts: an environmental impact assessment report, method selection information, and a product data sheet. By following guidelines and standards such as EN 15804:2012+A2:2019, these declarations ensure credibility since they have been independently verified (Boverket, 2019).

Manufacturers create EPDs in accordance with product specific guidelines, known as Product Category Rules (PCRs). These regulations, which are frequently created with trade groups, include instructions for carrying out life cycle assessments, including delimitation, method selection and data collection. By following PCRs keeps EPDs consistent among goods in the same category, which helps with well informed decision making about sustainable building techniques.

To put it in simple terms, the formula PCR (guidelines) + LCA (assessment) = EPD emphasizes how important established methods are to producing reliable and equivalent environmental product declarations (EPDs). Stakeholders my emphasize environmental sustainability in building projects by using EPDs to guide their decisions.

3.7. Impact categories

A vital process of assessing environmental impact is life cycle impact assessment (LCIA), which converts life cycle inventory (LCI) data into precise impact indicators. LCIA involves three main stages, including: First step, decide which impact categories to assess. Based on the subjects that they affect, these categories are usually divided into three broad divisions (see table below). Secondly, classifying the LCI data into several impact categories. Lastly, calculating the possible impact indicators (Mu et al., 2020, p. 18). In this study, the assessment focuses on the ecosystem impact category and the climate change (GWP Global Warming Potential) indicator.

Table 2: Impact categories (Mu et al., 2020)

Ecosystem impacts	Human impacts	Resource depletion
Climate change	Ozone depletion	Fossil fuel
Acid rain	Smog	Freshwater
Eutrophication	Particulate matter	Soil
Land use change	Carcinogens	Forest
Solid Waste	Toxicity	Grassland
Toxicity		Minerals

3.7.1. GWP – Global warming potential

The building sector is responsible for 36% of the global energy demand and more than one-third of total global greenhouse (CO2) gas emissions, hence why leading grading systems like LEED, BREEAM, and DGNB emphasize with these impact areas in the field of sustainable construction, highlighting the importance of GWP. This demonstrates the widespread industry awareness and significance given to GWP (Feng et al., 2023).

By absorbing energy and slowing down its release from the atmosphere, greenhouse gas emissions cause the earths temperatures to rise. These gasses are different from other gasses in terms of how long they will remain in the atmosphere as well as its radiative efficiency and ability to soak up energy (Vallero, 2019). The measure used to determine how well a greenhouse gas can trap heat in the atmosphere in comparison to another is called global warming potential, or GWP. The gas it is referred to is carbon dioxide (CO2) in accordance with the recommendations given by the Intergovernmental panel on Climate Change (IPCC, 2018). This decision gives an accurate framework for assessing the contributions various greenhouse gasses have made to global warming (Sussman, 2004).

3.8. Life cycle impact assessment

The life cycle impact assessment (LCIA) phase of an LCA evaluates potential environmental impacts based on the elementary processes (environmental resources and outputs) acquired during the LCI (Nieuwlaar, 2013). The life cycle impact assessment includes the following steps:

1. Choosing the appropriate impact categories.
2. Classification: Assigning elementary flows to impact categories.
3. Characterization: modeling probable impacts with conversion factors to get an indicator for the impact category.
4. Normalization (optional): describe potential implications relative to a reference.
5. Grouping (optional): sorting or ranking of impact indicators
6. Weighting (optional): relative weighting of impact categories, evaluation, and reporting.

3.9. Normalization and weighing

3.9.1. Normalization

A normalization process is essential in order to make it easier to compare different environmental impacts that are analyzed in different units. Normalization is combining and transforming the impact units into one single cohesive unit, to get a final result. In simple terms, this process turns random units into standardized scores (Ponsioen, 2014).

Normalization falls into two categories: “internal” or “external”, depending on the reference system used in the analysis. By using internal normalization, each environmental impact are divided by the overall total, average or the baseline result. External normalization on the other hand implicates dividing each environmental impact by a separate reference number, referred to the appropriate external normalization technique (Pizzol et al., 2017).

3.9.2. Weighing

Weighing is an non-mandatory part, performed after the normalization, of a life cycle impact assessment study as stated in ISO 14040 and 14044. The purpose of the weighing method is to combine the results of several impact categories into one singe number. To do this, numerical variables resulting from specific value-based decisions are used.

Since weighing requires the integration of social, political and ethical norms, its inclusion in LCIA has been a topic of continuous controversy (Huppes & van Oers, 2011). Despite the disputes, weighing is still a standard procedure in life cycle impact assessment since it makes the results more understandable for the average person.

3.10. LCA data

Evaluating the environmental impact of building service systems is a critical undertaking in the current discussion on sustainable construction methods. Numerous data sources that provide information about these systems' environmental impact are essential to this study. Environmental product declarations are one of these sources since they provide comprehensive data from thorough life cycle assessments. But today, finding an EPD may be difficult since the manufacturers don’t necessarily provide them. In order to assess the environmental impact in these cases, it is necessary to turn to other data sources such as generic data or building product declaration data.

3.10.1.Specific EPD data

Environmental product declarations (EPDs), which provide comprehensive data about the impact of individual items or systems on the environment, are essential sources of particular data. (Boverket, 2023c) for instance, points out that EPDs offer precise environmental impact data for products such as ventilation ducts. These EPDs are often available directly from manufacturers as well as through different databases that specialize in EPDs.

3.10.2.Generic data

The average environmental impact for rare product categories of are provided by generic life cycle assessment data. While specialized data from EPDs are providing more accurate information, generic data provides a rough estimate of the impact. When an EPD can’t be found, the generic data acts as a baseline for evaluating the environmental performance of different items. It’s important to consider that generic data usually shows average values across a product category, rather than precise data for individual items. Furthermore, a 25% margin is frequently included into generic data, in accordance with the Swedish Building Regulations (BBR), to accommodate for uncertainties and differences in real-world settings.

3.10.3.Building product declaration data

Building product declarations provides a breakdown including percentages of every material used in a building product. When it comes to evaluating the environmental impacts of some products, this data become crucial, especially in cases where EPDs are not accessible. Through an analysis of the percentages of materials used in the building goods declaration, one can now obtain important information on the composition of the product. With this information, its not possible to calculate the environmental impact of each material used in the product, by finding EPDs for the materials rather than the product itself.

4. Methodology

This chapter outlines the method used to examine the embodied carbon emissions associated with building service systems. The four primary steps, presented in detail below, are intended to systematically evaluate and quantify these systems' climate impact. The life cycle assessment guidelines ISO 14040 and ISO 14044 (ISO, 2006, 2006) serve as the foundation for the approach used in this study. By providing a thorough framework for carrying out life cycle assessments and environmental impact analyses, these defined standards not only ensure methodological consistency and dependability, but also a high degree of credibility and precision in its evaluations.

Step 1: Includes a comprehensive phase of data collection and analysis. The BoM lists (Bill of Materials - lists include information on the parts and products used in the ventilation, electrical, and plumbing systems) are created based on extracted data from BIM models, which are then used as the basis for further analysis.

Step 2: Involves a thorough analysis of emission factors. This entails carefully obtaining and examining environmental product declarations, generic data, and material compositions in order to determine the building service systems' embodied carbon footprint.

Step 3: Incorporates the calculations of the building service systems' embodied carbon footprint.

Step 4: Concludes with an analysis and validation of the projected climate impact emissions. This stage offers insightful information about how the analyzed systems are affecting the environment, making it possible to visualize and analyze the data, identify critical areas of improvement, and support the development of well-informed conclusions for the built environment.

Figure 6 below is a visual representation of the methodological workflow used in this study. Further information on each phase, including specific calculations and methods will be provided in this chapter.

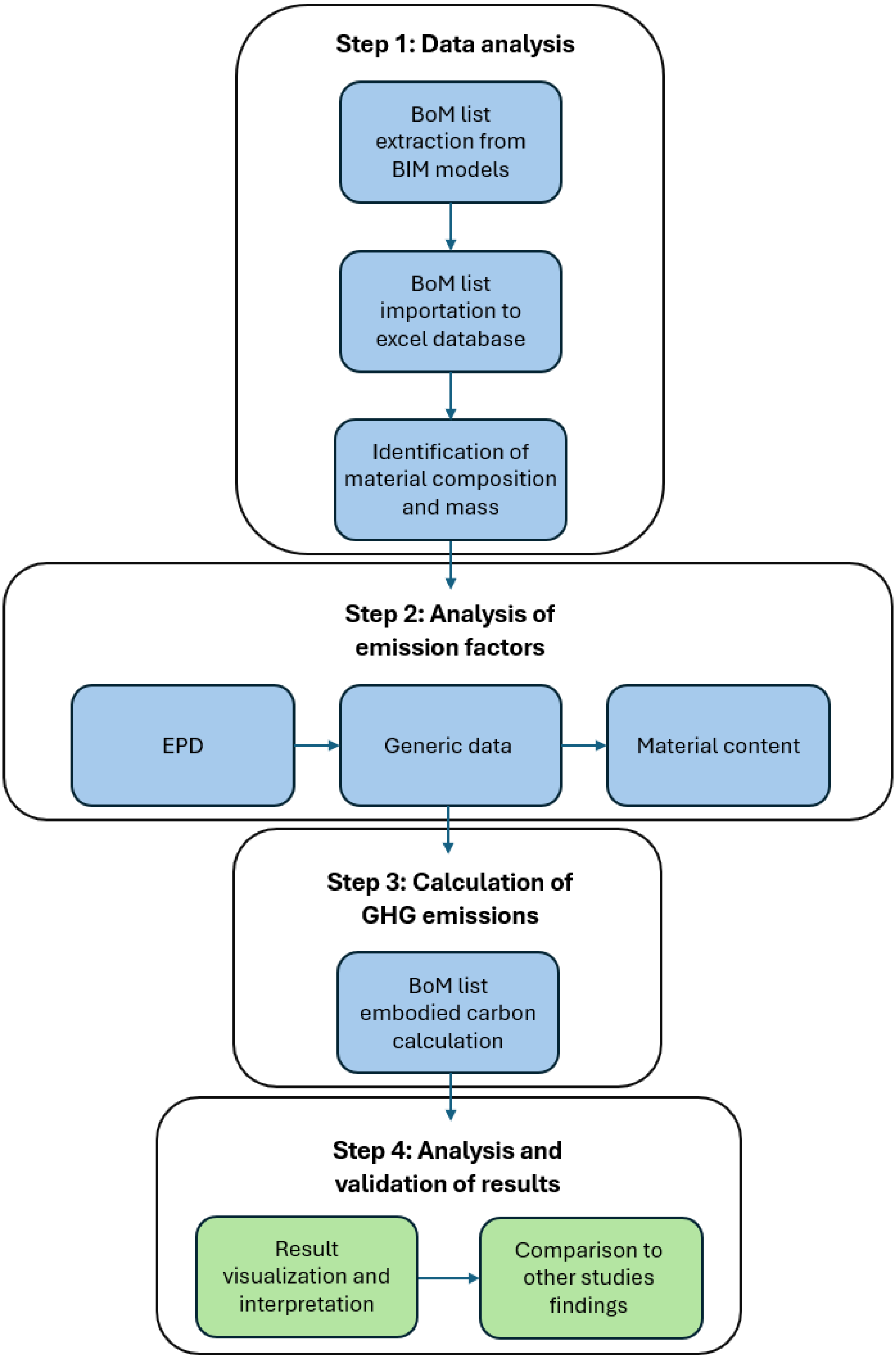

Figure 6: Methodological workflow of the study.

4.1. Case study

Located in Lund Sweden, a state-of-the-art Hedda's gymnasium (see Figure 7) consists of five buildings on four levels, one of which is located underground. The building project started in late 2020 and opened its doors around 30 months later. The project had a large budget, estimated at SEK 630-650 million, and it covers an area of 25000 square meters. The idea behind this project came from Lund Municipality's goal of giving residents an outstanding educational facility. Aart Architects Sweden was given the opportunity to create structures that carefully combined architectural beauty and practicality in order to achieve this goal. The project general contractor, Skanska Sweden, adeptly orchestrated each stage of construction together with the contributions of Structor Kristianstad, who served as the designer, Assemblin Installations handled the HVAC, Assemblin VS handled the electrical installations, Lundströms Golv handled the flooring, and Rolleryboys Måleri took care of the paintwork.

Assemblin is interested in the study's findings because, as explained in Chapter 1, they are taking a proactive stance against forthcoming Boverket regulations. For the purpose of guaranteeing compliance and early adaptation to changing regulatory frameworks, they are actively getting ready to calculate the embodied carbon of buildings and their systems.

Figure 7:Hedda Anderssongymnasiet (Aart.dk)

4.2. Data gathering

Assemblin oversaw the collection of data for the buildings service systems, by extracting information out of the building information models (BIM) in a form of a bill-of-material (BoM) list. These lists included information on the parts and products used in the ventilation, electrical and plumbing systems. The method of gathering data was essential to the research since it laid the groundwork for the climate impact calculations. The journey started with a thorough examination and arrangement of the BoM lists for each system, make sure that there was no information missing or misplaced. The BoM lists underwent a thorough processing step, in order to extract the necessary information such as product models, quantities, manufacturers, and specific names. This data was then collected into an extensive database, providing the foundation for further assessments.

Thorough searches were then carried out on the websites of the manufacturers, using the database as a guide to gather information on weights of the products, material compositions and environmental product declarations (EPDs) that were accessible.

If this data was not available online, efforts were made to reach out to the manufacturers in order to receive the absent information. Generally, when EPDs were not available, generic data or material composition information were used to calculate the climate impact under particular conditions. In order to ensure clarity and integrity in our study, Chapter 5 will place a strong emphasis on transparency, expressed in graphs, about the selection and usage of EPD and generic data in the study's calculations. Due to the minimal usage of the BPDs and because they always were used in combination with EPD or generic data, they were excluded from these graphs. In cases where BPDs were used, the data was registered as EPD or generic data in the graphs, depending on what data had been used. This approach is used since the emission factors are provided by either EPDs or generic data. BPDs don't directly add to the emission variables that are of interest in this study, but instead they provide information on the elements and their amounts used to produce a particular product.

The weight of each component was determined in order to accurately calculate the embodied emissions of the system. To achieve this, product-specific information must be obtained directly from the manufacturers, including details on product sourcing and manufacturing emissions. Finally, a comprehensive evaluation of the ventilation system's climate impact was accomplished by working with manufacturers and closely examining the component's specifications.

4.3. Method of climate impact calculation

In order to determine the environmental impact with precision and accuracy, we utilized three different approaches, each dependent on the data from the manufacturers that were available. Certain categories of climate data were given priority to the building's climate impact estimates. The following lists the recommended sequence of data sources and the corresponding databases for each:

1. Environmental product declaration (EPD)
- epdhub.com
- epd-norge.no
- environdec.com
2. Generic data
- Boverket.se
- CO2data.fi
3. Building product declaration (BPD) and EPD
- Manufacturer-issued BPD

Of these strategies, using the EPD is the most effective and accurate option. EPDs provides important data of the product that are being analyzed. The climate impact was then calculated by using the EPD data and the product weigh from the database, using the formula below. The different units in which the EPDs were reported were mostly kilograms of CO2 equivalent per kilogram of product. Other quantities were also frequently found, such as kilogram of CO2 equivalent per product. In these cases, the number of items was used to determine the climate impact, see equation 1.

Equation 1:

$$Environmental\ impact\ (kgCO_2 equiv.) \\ = Product\ [kg, m\ or\ pcs] \times EPD\ climate\ data\ \left[\frac{kgCO_2}{kg, m\ or\ pcs}\right] \quad (1)$$

The study resorted to using generic data sources when the environmental product declarations were not accessible. To assess the products' environmental impact, this method uses industry averages or generic data sets, see equation 2. The generic data sources offered fundamental information of the typical environmental impacts associated with similar items or products, even if they are not as accurate as using EPDs. Using this method, general data sets pertaining to the kind of product and emission factors are then extrapolated from these sources.

Equation 2:

$$Environmental\ impact\ (kgCO_2equiv.) = \ Product\ [kg] \times Generic\ data\ \left[\frac{kgCO_2}{kg}\right] \qquad (2)$$

Finally, in cases where the product itself did not have an EPD nor generic data available, a different calculation method based on the building product declarations (BPDs) was used, see equation 3. With this approach, the materials utilized in the products composition and their corresponding weight contribution to the component was assessed. Even in the lack of EPDs or generic for the final product, this method allows a comprehensive investigation of the environmental performance of the products component parts. This method evaluates the environmental impacts of each material used to the parts of the product, instead of the whole product itself, by identifying EPDs or generic for the individual materials/parts instead of the final product. Although this method might not be the most accurate way to assess the environmental impact, it was the next best option available. It is noteworthy that this method assesses the impact of the material creation alone, without considering aspects like final product assembly and its transportation.

Equation 3:

$$\begin{aligned} &Environmental\ impact\ (kgCO_2equiv.) \\ &\qquad = \left(Material\ 1\ [\%] \times EPD\ climate\ data\ 1 \left[\frac{kgCO_2}{kg}\right]\right) \\ &\qquad + \left(Material\ 2\ [\%] \times EPD\ climate\ data\ 2 \left[\frac{kgCO_2}{kg}\right]\right) \ldots \\ &\qquad + \left(Material\ X\ [\%] \times EPD\ climate\ data\ X \left[\frac{kgCO_2}{kg}\right]\right) \times Product\ [kg] \qquad (3) \end{aligned}$$

Table 3 below gives an example of calculating the climate impact with equation 2. K EC is a circular duct fan, which according to the material breakdown of the product provided by the manufacturer (Flakt group), consists of three parts: The cover, which participates with 50% in the total amount of the product, the engine chassis 48% and potentiometer with 2%. The participation percentage of the materials is multiplied by the climate data and the final environmental impact for 1 kg of K EC is 3.69 kg CO_2 equivalent.

Table 3: K EC circular duct fan (Environmental impact calculation)

K EC								**3,69**
50%			48%			2%		
Cover	%	kg CO_2 eq	Engine Chassis	%	kg CO_2 eq	Potentiometer	%	kg CO_2 eq
Galv. plåt (AluZink)	100	2,91	Aluminum	5	7,2	Cu	16	5
			Copper	11	5	PBT	52	3,93
			PVC	2	2,39	epoxy	12	4,9
			Polyamide 6	13	6,5	Metal ceramics (Al)	20	5,7
			glass fiber	6	2,69			
			Iron	38	4,1			
			epoxy resin	15	4,9			
			iron oxide	6	2,69			
			NBR	4	1,64			
Total:		2,91	Total:		4,48	Total:		4,57

4.4. Material inventory

The foundation of the assessment consisted of the careful extraction of the building service system's bill of material (BoM) lists from the BIM models. These BoM lists were divided into categories in order to improve the organizational effectiveness and to speed up the procedure meanwhile guaranteeing and organized approach to the study.

The BoM lists were first divided into three primary categories: Electrical, ventilation and cooling, and plumbing systems. This strategic workflow was created in order to focus on one separate system at a time, which made it easier to conduct a more thorough and navigated assessment.

Additionally, the BoM lists were divided into subcategories within each specific category. This extra layer of categorization enabled an examination of the many elements and components of the systems in more detail and provided a more comprehensive analysis. The workflow was made simpler overall by improving the BoM lists' clarity and structure throughout the assessment of various elements to their appropriate subcategories. This methodological approach allowed team members engaged in the study to collaborate more easily and navigate the large datasets with ease.

4.4.1. BoM-list of the ventilation system

Materials for the ventilation system include several essential components necessary to control airflow and maintain air quality in the facility. Air handling units (AHUs), fans, diffusers, dampers, silencers, ducts, and other relevant parts are among those involved. According to the BoM list provided by Assemblin (see Table 9 in the Appendix) Ventilation systems count 6,798 items. These components of the BoM are constructed from a variety of materials, including galvanized steel, aluminum, plastic, and mineral wool. The choice of materials is influenced by several factors, such as cost-effectiveness, durability, and thermal capabilities. For example, because of their strength, robustness, and resistance to corrosion, galvanized steel, and aluminum are frequently used throughout the building for ducting and other structural components, and plastic components because of their lightweight and simple installment. Moreover, insulation materials are frequently used because of their superior sound absorption as well as thermal resistance qualities, especially in ductwork linings and silencers.

A graphic description of the parts that make up the ventilation system at Hedda Gymnasium is shown in Figure 8, demonstrating the weight distribution of the system. The system's performance and design may be optimized with the use of this breakdown, which also helps to determine the relative value of each component.

Table 4 below offers a thorough description of each category within the ventilation system as well as its content.

Table 4: Ventilation system inventory.

Category:	**Description:**
Circular duct	*Circular ducts*
Circular duct detail	*Bends, joint parts, plugs, reducers, expanders, and branches*
Rectangular duct	*Rectangular ducts*
Rectangular duct detail	*Bends, joint parts, plugs, reducers, expanders, and branches*
Silencers	*Silencers*
Diffusers	*Exhaust-, extract-, and supply-air devices*
Dampers	*Flow and fire dampers*
AHU's	*Roof and duct fans, air handling units, and other components*
Insulation	*Absorption and insulation materials*
Other	*Boxes, covers, filters, measuring devices, and other components*

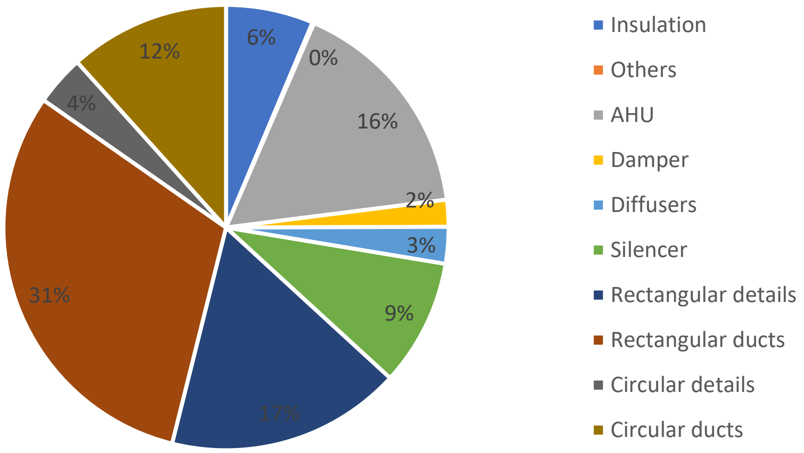

Figure 8: Hedda Gymnasium's ventilation system weight distribution (Calculated from BoM lists provided by Assemblin).

4.4.2. BoM-list of the electrical system

The building's electrical system is made from a wide range of parts and components essential for the system to operate at its full potential, such as outlets, cables, switches, light fixtures, and other necessary parts associated with its infrastructure, as further described in table 5. According to the BoM list provided by Assemblin (see Table 9 in the Appendix) Electrical systems count 222,205 items and 252,654 m of cable and channelization. These parts are made from a variety of materials, including copper, aluminum, and metal alloys, which are chosen according to safety regulations, conductivity, and durability. It is important to highlight that this research primarily assesses the main electrical components due to the limitations in the availability of environmental and product data discussed in the limitations section.

The table below provides a more detailed inventory of the electrical system's categories and its parts and components included in this study.

Table 5: Electrical system inventory

Category:	**Description:**
Cable channelization	*Protecting pipes, tubes, cable channels, installation/connection parts*
Wiring	*Electrical installation cables*
Electrical equipment	*Distribution accessories, measuring devices, centrals, and batteries*
Appliances	*Switches, adapters, outlets, and connection boxes*
Luminaries and light sources	*Outdoor and indoor lighting accessories, fixtures, frames*
Other	*Filters, measuring devices, tele, security, and other*

4.4.3. BoM-list of the plumbing system

The plumbing system includes a wide range of parts and components, such as pipes, fittings, valves, boilers, radiators, and other related infrastructure, that are necessary for the building's hot water supply, heating, and wastewater management systems to operate properly. According to the BoM list provided by Assemblin (see Table 9 in the Appendix) Plumbing systems count 46,397 items. The main upcoming materials utilized in these systems include steel, copper, brass, plastics, and other metal alloys. These well-known materials are chosen with the reliability as well as effectiveness of the entire system in mind, taking into account factors like thermal conductivity, durability, and resistance to corrosion.

The weight distribution in the plumbing system of the Hedda Gymnasium is shown in Figure 9, which provides a detailed breakdown of its constituent parts. This visualized breakdown clarifies the relative importance of each component.

Table 6 below provides a more detailed inventory of the categories and products included in this study.

Table 6: Plumbing system inventory

Category:	**Description:**
Sewage	*Pipes, fittings, seals, valves, outlets, etc.*
Domestic water	*Pipes, fittings, valves, seals, bath/shower mixers, etc.*
Domestic hot water	*Pipes, fittings, valves, seals, bath/shower mixers, etc.*
Heating systems	*Radiators, pipes, fittings, pumps, valves, sensors, etc.*

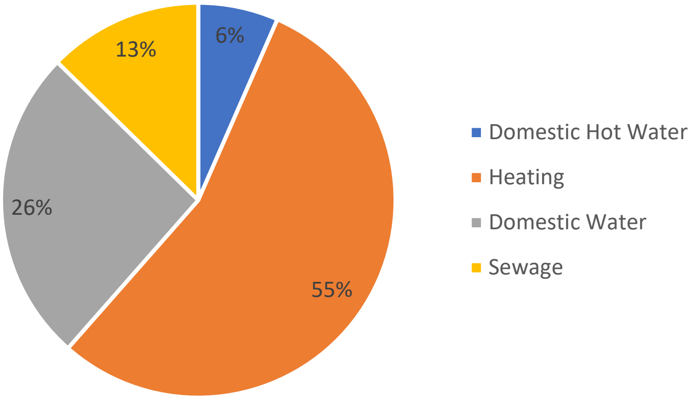

Figure 9: Hedda Gymnasium's plumbing system weight distribution (Calculated from BoM lists provided by Assemblin).

4.5. Validation of data

A thorough validation procedure was used to guarantee the validity and dependability of the embodied carbon findings. This required comparing the findings against data from other reference studies that used comparable techniques and looked at related research topics. A thorough selection of pertinent research was made, and a methodical comparison was carried out to look at both general trends and particular measurements. To determine possible sources of variance, all discrepancies and inconsistencies were closely examined. Chapter 5 of the thesis will go into further detail about this validation process and its findings.

4.6. Hotspot analysis

When the results were calculated and validated, a hotspot analysis was performed in order to determine the worst-performing category, the hotspot, of the building service systems. The data was then gathered and sorted based on how it contributes to the climate impact and the main hotspots of the systems were established by ranking the GWP of each category. Finally, an examination of the current supply of environmentally friendly material options for the worst-performing category was carried out to identify the CO_2 reduction potential of replacement.

4.7. Goal and scope

With an emphasis on stages A1 to A3 of the lifespan of the building, this study aims to investigate the bill of materials related to the ventilation, electrical, and plumbing systems throughout the Hedda Gymnasium. This study's specific goal is to calculate the amount of embodied carbon there are within these systems and their components. The research looks at future regulations that BBR Boverket has suggested, such as the projected emission limitations for new construction by 2027 and uses a thorough analysis of the embodied carbon emissions to determine the main contributor to the climate impacts of these systems. In addition to this, the research also seeks to ensure that the efficiency and indoor environment of the facility are not jeopardized by any modifications implemented to lower carbon emissions. The study will suggest improvements in material choices or systems with lower embodied carbon emissions that could serve as mitigation solutions in line with the goal of the Paris Agreement.

4.8. Functional unit

The total climate impact was expressed in terms of kilograms of carbon dioxide (CO2) equivalent per square meters (m^2) of gross floor area (BTA), in accordance with BBRs guidelines (Boverket, 2023). This unit includes the cumulative effect of greenhouse gas emissions excluding biogenic carbon dioxide removals and emissions. This unit was chosen in order to be able to compare the results between different buildings, regardless of their size or function.

4.9. System Boundaries

A thorough effort has been taken in setting the limitations for this research, down to the component level. This approach goes beyond the simple system categorization and includes a thorough analysis of the individual components that create the facility’s ventilation, plumbing, and electrical systems. With a focus on the many complexities present in these systems, this detailed study seeks to provide a comprehensive evaluation of each system's embodied carbon emissions.

All materials and parts directly used for the operation and function of each system fall inside these defined system boundaries. For the electrical system, this includes wiring electrical panels, switches, outlets, lighting fixtures, motors, and control devices; for the plumbing systems, it includes boilers, pumps, radiators, pipes, fittings, valves, and insulation materials; and finally, for the ventilation system, it includes air handling units, ductwork, diffusers, fans, filters, dampers, and insulation material.

By these boundaries, each component can be thoroughly assessed, leading to a precise calculation of the embodied carbon emissions of each system. In addition to this, it also makes it possible to identify the parts within each system where interventions might be most effective to reduce the total carbon footprint.

The building life cycle analysis conducted in this study is limited to the production stage A1 (raw material extraction), A2 (transportation), and A3 (manufacturing), following EN 15978 (*EN 15978*, 2011) as seen in Figure 10 below. This methodological technique complies with accepted practices and enables somewhat uniform communication, making the study comparable and compliant with declarations and public databases.

With a primary focus on the production stage, this research seeks to offer a thorough understanding of the embodied carbon located in technical building service systems, materials, and components.

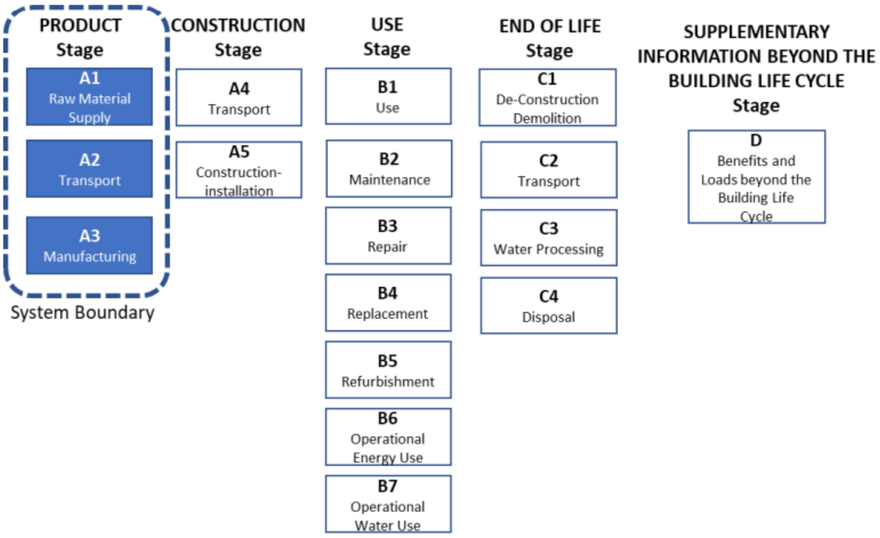

Figure 10: System Boundary (CEN 2011)

4.10. Limitations

It is important to recognize that several constraints have impacted the width and depth of the research while doing this study on the embodied carbon of a building's service systems. These restrictions are mostly due to the lack of data, especially concerning the building’s electrical infrastructure components.

As discussed in the introduction of this research, it is important to consider the embodied carbon footprint to conduct sustainable building practices. However, in order to do so, environmental data from the building product manufacturers needs to be available. With this said, significant research on embodied carbon for ventilation, and plumbing systems was discovered through the literature assessment. The literature review also revealed large data gaps that were currently accessible regarding the electrical components of the buildings.

The embodied carbon data of several electrical components, including cables, protective tubes, switches, outlets, light fixtures, tele systems, data equipment, fuses, boxes, and pipes were found and was thoroughly assessed as a part of the methodology. These elements were considered being essential to the electrical system’s operation and make up for the main electrical infrastructure of the building. However, tiny connection parts, plastic fittings, frames, tightening mechanisms, rubber components, and other similar parts were not included in the study due to the data gaps earlier mentioned.

The lack of thorough data for these smaller electrical components led to the decision of restricting the assessment to the main electrical components. The absence of data for these components was a major barrier, in contrast to the systems for ventilation, and plumbing, where data were more easily accessible and thorough. Therefore, within the limitations of the data at hand, focusing on just the primary electrical components enables a more accurate and trustworthy evaluation, instead of using all generic environmental data and estimations of product weight.

However, although the embodied carbon footprint of the major electrical components may be more clearly recognized because of this study, it is still important to take into account that the completeness and accuracy may be compromised to some extent if the minor components are left out. The total embodied carbon linked to the buildings electrical system, may be underestimated because of this neglection. Despite these drawbacks, the study still adds to the expanding volume of information on embodied carbon in built environment and emphasizes the significance of additional research needed in order to fill in the data gaps and generally improve sustainable building methodologies.

Information regarding included components for respective building service system will be presented in figures 10, 14, and 17 further down below.

4.11. Assumptions

In order to get past the data restrictions and make the assessment of embodied carbon emissions related to the building service systems at Hedda Gymnasium manageable, a few assumptions were made along the way in order to carry out this study while still proclaiming accuracy.

One key assumption was the approximation of product weight in cases where specific product data were missing. For example, weight was at time calculated based on dimensions and material-based densities or similar product weight were used when the weight of some items were unavailable.

Furthermore, in situations where environmental product declaration data for specific materials and products were not available, assumptions were made based on the notion that materials or products with similar characteristics and use would have comparable environmental impacts that could be used in order to make up for the data gaps.

Similarly, when environmental product declarations were not accessible, additional assumptions were made in order to calculate the climate impact based on building product declarations. In these instances, lower amounts of product materials (less than 2%) were neglected, and the primary product body materials were evaluated, in order to make the process faster. To evaluate the main product body materials, EPDs were sought and used for those specific materials. Within the limitations of data at hand, this approach produces a conclusion that was relatively accurate even if it could have added some uncertainties.

While these assumptions help the assessment process in situations where information about the products are missing, they also introduce uncertainties that may impact the accuracy of the results. While conducting a credible and robust LCA study, it is essential to understand the nature of the assumptions, their sources, and implications.

5. Results

The wide range of materials used in the building of the ventilation, electrical, and heating & sanitation systems is the main cause of the significant embodied carbon content found in these systems. Because of their unique qualities and functions, each of these materials has been chosen to enhance the overall performance and efficiency of the MEP systems. Aluminum is often used in MEP systems for parts like motors and heat exchangers because of its great heat transfer qualities and lightweight design. Because of its great conductivity and resistance to corrosion, copper is frequently used in MEP systems' interior pipes. It is essential to guarantee the dependable operation of plumbing and electrical components because of its capacity to tolerate the corrosive impacts of different fluids and conduct electrical currents properly. Steel, a strong and adaptable material, is used widely in MEP systems for a variety of purposes, including ducting, support rails, and enclosures. Because of its exceptional strength-to-weight ratio and ability to withstand corrosion, this material is essential for maintaining the structural integrity and long-term viability of MEP systems. Cast iron is a common choice for piping in MEP systems because of its strength and resistance to high temperatures and pressures. Because of the material's durability and resilience, it works well for moving fluids through challenging working environments, assuring the dependable and effective operation of plumbing systems. Moreover, performance and efficiency in MEP systems may be optimized by the integration of different metal combinations in boilers and chillers (CIBSE, 2014).

The thoughtful selection and use of these materials within MEP systems highlight the complex nature of the infrastructure seen in contemporary buildings generally. Further examination of the individual data-driven results, along with a look at the embodied carbon concentration of each of these components, will take place in this chapter. Outlining the contributions of specific materials to the total embodied carbon footprint of the MEP systems.

Understanding the embodied carbon footprint of building systems is essential for the development of sustainable building techniques. Within this framework, the ventilation system is significant and has a major effect on how a building impacts the environment. This section aims to shed light on the results of a thorough investigation of the embodied carbon emissions caused by Hedda's building service systems.

The approach used in this research combines insights from building product declarations, generic data, and environmental product declarations, which are presented in the previous chapter. By using this approach, the results are aimed to highlight the importance of material choices, production process, and system optimization with accuracy in order to reduce the building's carbon footprint.

5.1. Ventilation system

Analyzing the embedded carbon emissions in Hedda's ventilation system provides valuable insights into how its many parts affect the environment.
The climate impact distribution within Hedda's ventilation system's various categories is shown in Figure 11 below. Notably, the calculations of Hedda's ventilation system show that 43% of total carbon emissions consist of duct systems. The aggregates account for 37% and come just behind. There are several reasons why the duct systems and aggregates categories are so important to the climate impact. For example, duct systems have a high embodied carbon because they frequently need huge quantities of metal manufacture and installation. Aggregates include components such as air handling units, roof and duct fans, and other similar parts. These may be significant sources of emissions due to various factors related to their manufacture, transportation, and installation. Even if the climate demand percentages in other categories are lower, their cumulative influence shouldn't be ignored. However, because of their significant role in total emissions, the focus will be on the duct system and aggregate categories.

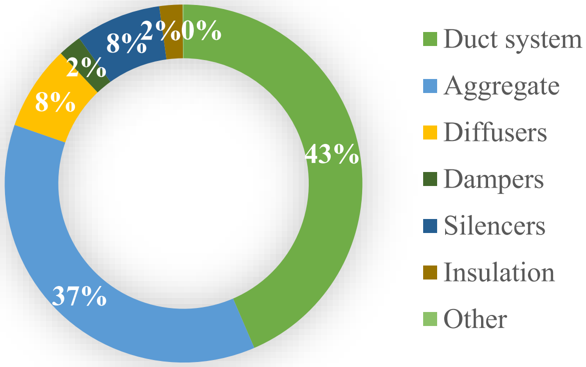

Figure 11: Climate impact distribution within Hedda's ventilation system categories.

The following visualization provides a comprehensive illustration of the estimated Global Warming Potential (GWP) for each category in the ventilation system throughout life cycle stages A1 to A3, represented in kilos of CO2-equivalent. A better understanding of the carbon intensity linked to different components may be obtained from this figure. Major variations in carbon emissions between the various groups are visible upon closer inspection. By examining these results, important information about certain areas that need to be addressed and modified to reduce the adverse climate impact of the ventilation system was obtained.

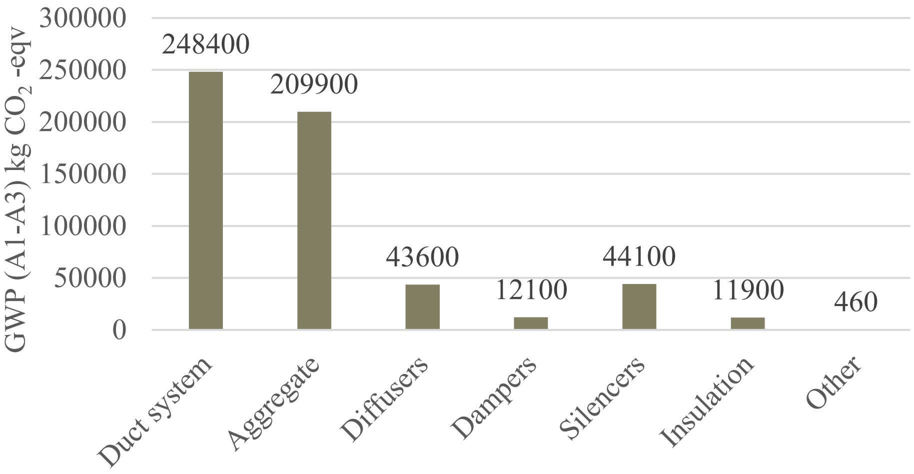

Figure 12: Calculated climate impact (A1-A3) for Hedda's ventilation system categories.

An extensive summary of the embodied carbon emissions per square meter in the ventilation system is shown in Figure 13 below. As can be seen, and in line with earlier findings, aggregates and duct systems are the main sources of the system's climate impact. It also determines the overall amount of embodied carbon within all the categories, which comes out to be about 23-kilogram CO_2 equivalent per square meter (kg CO_2 eq./m^2). This number, which is consistent with industry standards, provides important information about the ventilation system's total carbon impact and highlights the importance of reducing emissions from aggregates and duct systems.

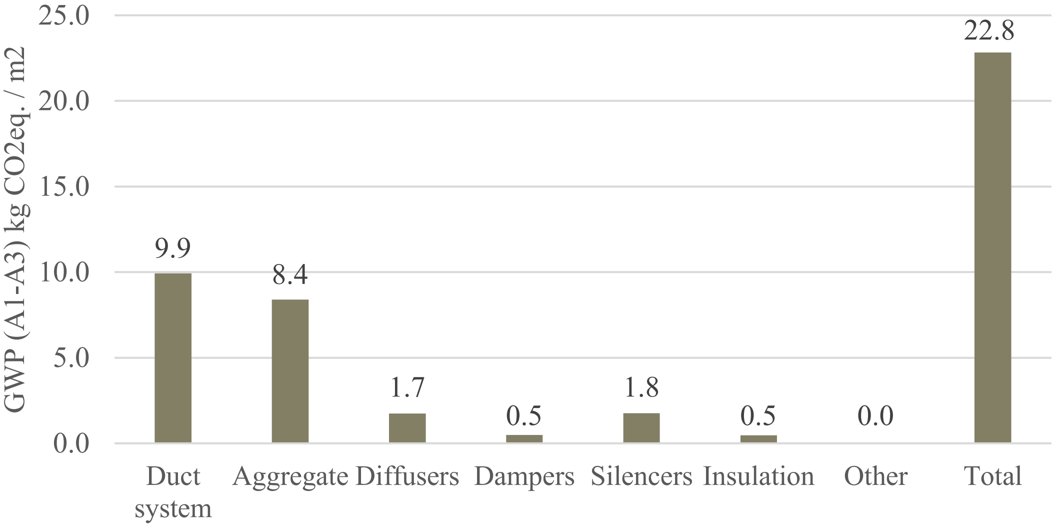

Figure 13: Calculated climate impact (A1-A3) per square meter of the Hedda's ventilation.

5.1.1. Climate data sources of the Hedda's ventilation system calculations

Figure 14 below displays the distribution of the calculated climate impact from EPDs and generic data. To provide a thorough study, generic data were used in addition to EPDs due to the data availability limitations. EPDs provide more accurate data, but to close gaps and give a more comprehensive picture of the climate impact of the building's electrical systems, generic data had to be included. The use of BPD (building product declarations) was excluded from this data-chart, since they don't directly add to the emission variables that were of interest within this study. In cases where BPDs were used, the data was registered as EPD or generic data, depending on what emission data source had been used in combination with the BPD.

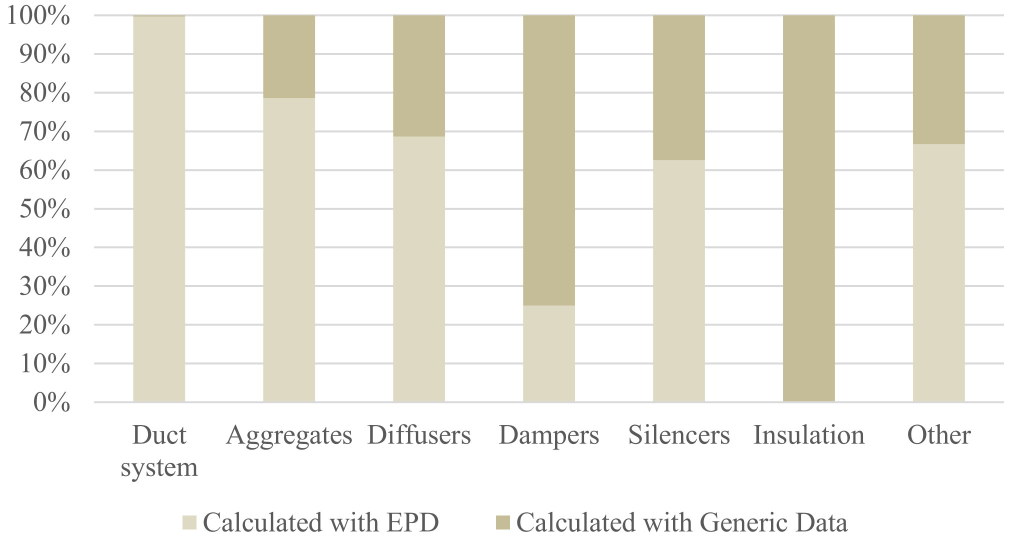

Figure 14: Climate data sources of Hedda's calculated ventilation components.

5.2. Electrical system

The electrical system in Hedda is the subject of the following sections, which focus on assessing the embodied carbon emissions related to its many components. The goal of the electrical system inquiry is to offer an extensive understanding of the different part's impact on the environment. Practices for following projects may be advised and areas that could use improvement can be found by analyzing the contributions of these various categories and components.
The evaluation of Hedda's electrical system is essential to comprehending its climate impact. However, there were difficulties, because of data gaps and lack of environmental data available. Even with extensive data collection efforts, these gaps made it difficult to determine the system's climate impact with accuracy. This hindered accurate assessment of the embodied carbon emissions related to the building's electrical system. However, the climate impact was still calculated for the electrical systems and distributed to categories, but due to the data restrictions, only for parts of the categories, as shown in Figure 15 below.

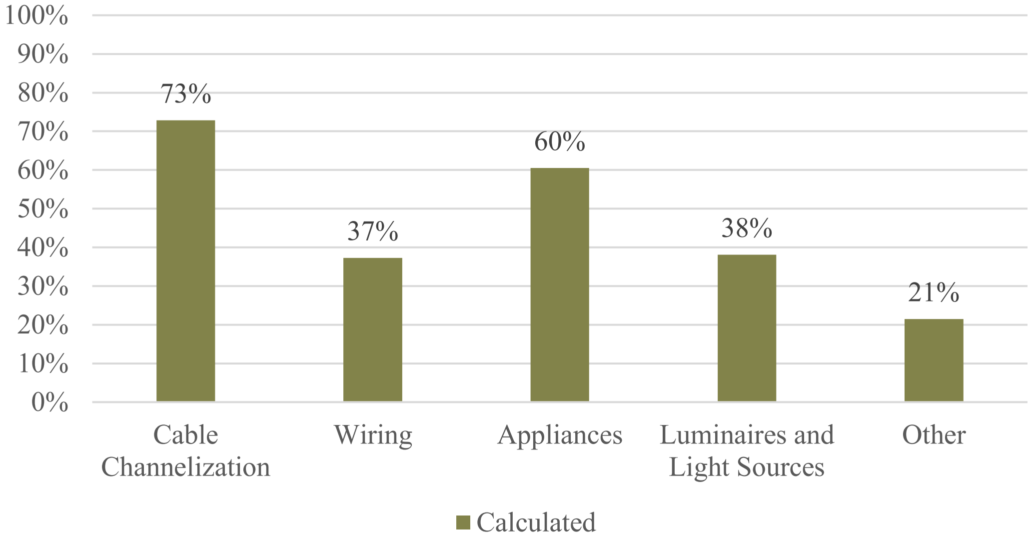

Figure 15: Distribution of climate impact (A1-A3) calculated in Hedda's electrical system.

The results show, as seen in Figure 15, that 73% of the total amount of parts and components of the cable channelization-, 37% of the wiring, 60% of the appliances, 38% of the luminaires and light sources, and 21% of the other categories, were still managed and analyzed. These percentages represent only the number of elements calculated from the Bill of Materials (BoM) for Electrical systems, and they differ from those in the Ventilation and Plumbing systems. For ventilation and plumbing systems, similar charts represent percentages of calculations according to the weight of the products. Even though the assessment might be incomplete, it still offers insightful information on embodied carbon emissions connected to the electrical systems components. Even if the study is not fully completed, these results provide a basis for understanding the climate impacts of the electrical systems and pinpointing areas that may be improved in the following projects.

5.2.1. Climate data sources of the Hedda's electrical system calculations

Figure 16 below visualizes how each of these climate data sources contributed in proportion to the calculated climate impact (shown in Figure 15). The use of BPD (building product declarations) was excluded from this data-chart, since they don't directly add to the emission variables that were of interest within this study. In cases where BPDs were used, the data was registered as EPD or generic data, depending on what emission data source had been used in combination with the BPD.

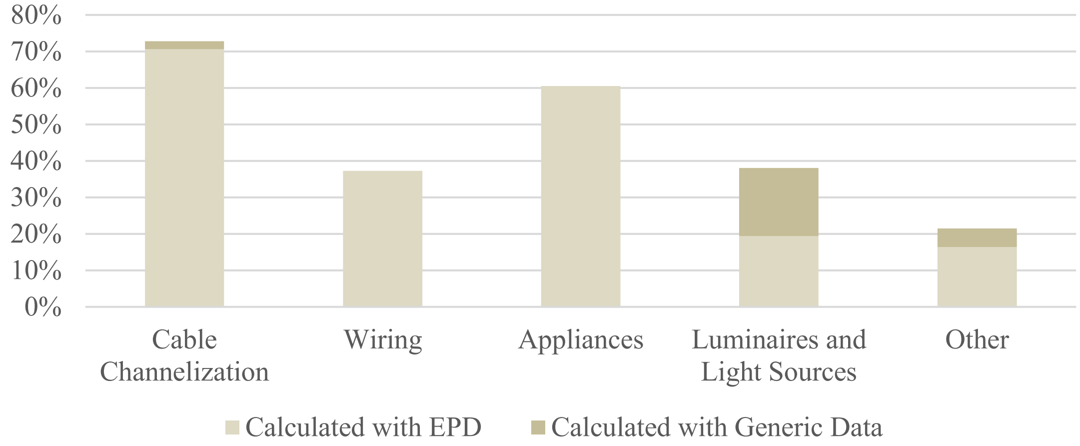

Figure 16: Climate data sources of Hedda's calculated electrical components.

Recognizing that the data analysis is still incomplete is crucial given the status of the investigation. Although significant advances have been achieved in defining the embodied carbon footprint of the electrical system components, several areas still lack sufficient data, as shown in Figure 15. Consequently, the conclusions offered here provide a preliminary view of the embedded carbon emissions related to the electrical system, with the understanding that more study and refinement would be required when more data becomes available. The following section acknowledges the constraints imposed by incomplete data coverage and presents an overview of the preliminary findings and insights obtained from the research. However, Figure 17 below presents the climate impact of the calculated electrical part.

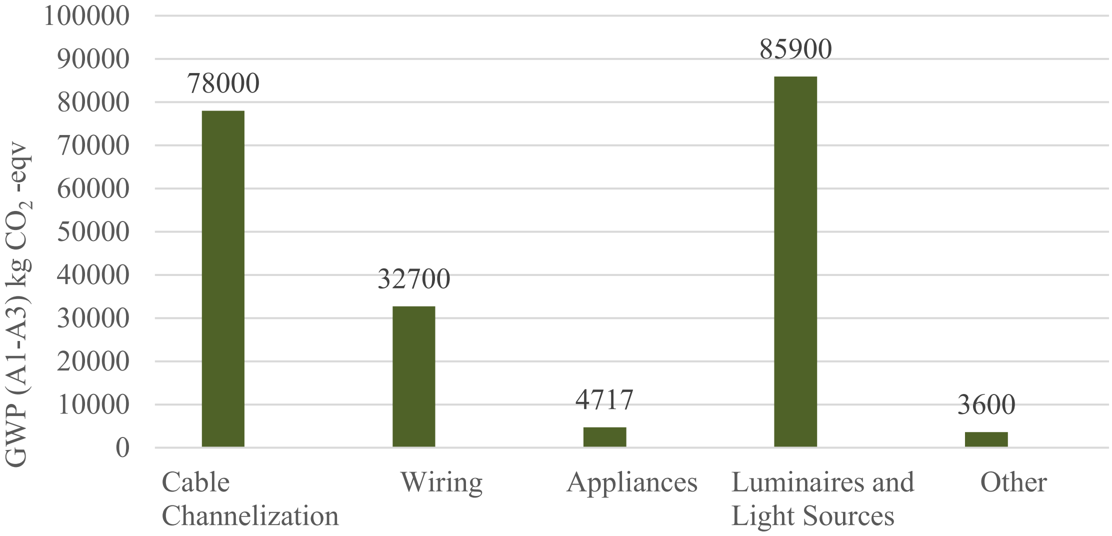

Figure 17: Calculated climate impact (A1-A3) for Hedda's electrical system categories.

5.3. Plumbing system

The gymnasium's carbon-embodied plumbing systems will be addressed in this section. The climate impact of these elements is investigated through a thorough examination, providing insight into their carbon footprint and possible routes toward sustainability.

Figure 18 below represents how the plumbing system's various categories are distributed according to how they impact the climate. With 59% of the total climate impact within the plumbing category, the heating system category stands out as having the greatest climate impact. This dominance may be due to the usage of materials that are known for having high greenhouse gas emissions, such as steel, copper, and aluminium. The category of domestic water systems comes in second, making up 20% of the total impact. Domestic hot water systems hold up the remaining 9% of the category, with the sewage system category the remaining 12%.

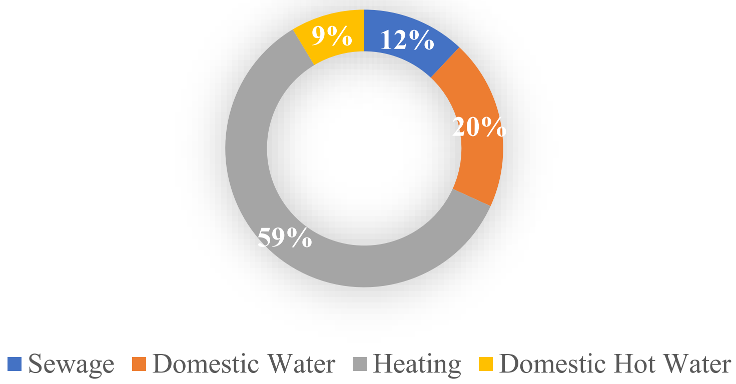

Figure 18: Climate impact distribution within Hedda's plumbing system categories.

Figure 19 illustrates the embodied carbon emissions (kg CO2 eq.) for different categories of the plumbing system. It is apparent from the data that heating systems have the greatest climate impact, and this is notably evident in the figure below. This result corresponds to the previous findings that the materials used in the heating system category have a major adverse effect on the environment. The domestic water systems also contribute a great deal to the carbon footprint. In contrast, the emissions from the sewage- and domestic hot water system categories are comparatively smaller, but they are still noteworthy when considering sustainable construction methods.

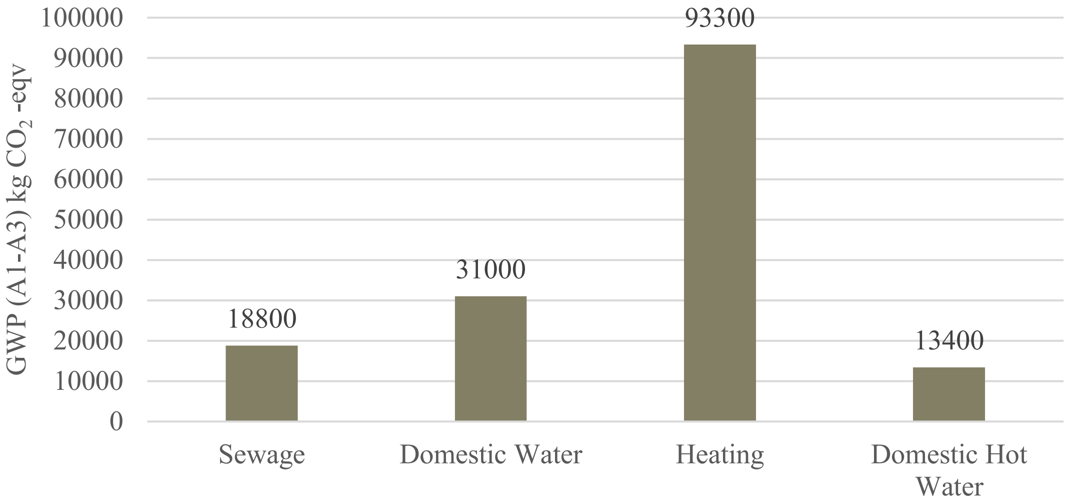

Figure 19: Embodied carbon emissions (kg CO2 eq.) for each category of Hedda's plumbing system.

Figure 20 shows the carbon dioxide equivalent emissions per square meter (kg CO2 eq./m^2) of the plumbing systems. This measuring unit makes it easier to compare the results with other buildings, which promotes a more comprehensive understanding of the environmental performance.

It is projected that the plumbing systems embodied carbon emissions are 6.3 kg CO2eq./m^2 in total. This amount is significantly lower than the ventilation system emissions, which came to 22,8 kg CO2eq./m^2. The significant difference between the heating and plumbing systems emphasizes the possible areas for targeted sustainable interventions as well as the differing environmental consequences connected to various building service system components. In the conclusion section, these differences will be covered in more detail, along with some thoughts on how these discoveries may affect future research and sustainable construction techniques.

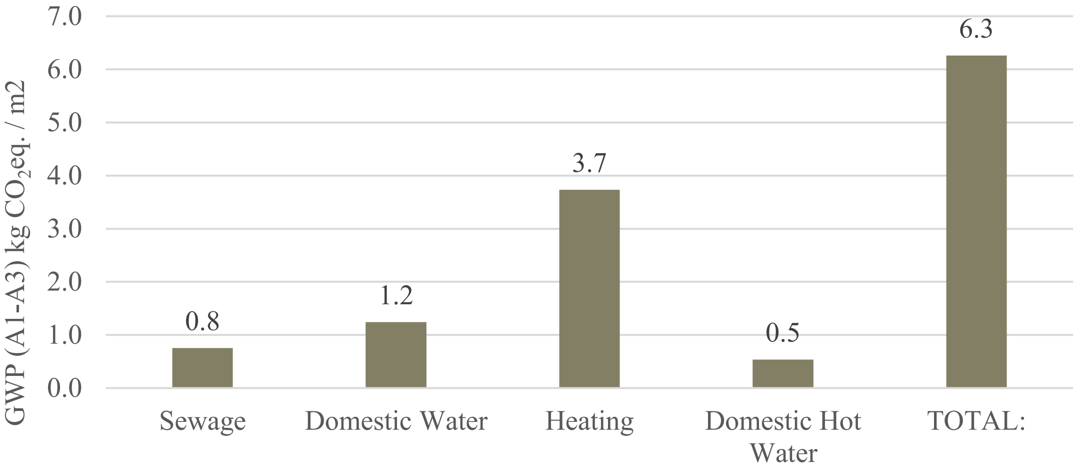

Figure 20: Plumbing climate impact (A1-A3) per square meter of Hedda's building.

5.3.1. Climate data sources of the Hedda's plumbing system calculations

A detailed analysis of the contribution of each environmental data source to the final climate impact is shown in Figure 21. Although there were not many Environmental Product Declarations (EPDs) for these systems that were found throughout the search, a large amount of generic data was found and used. The use of BPD (building product declarations) was excluded from this data-chart, since they don't directly add to the emission variables that were of interest within this study. In cases where BPDs were used, the data was registered as EPD or generic data, depending on what emission data source had been used in combination with the BPD. This breakdown emphasizes the availability of the data while also clarifying its nature. This study strengthens the evaluation's credibility by offering insights into the dependability and reliability of the results reached.

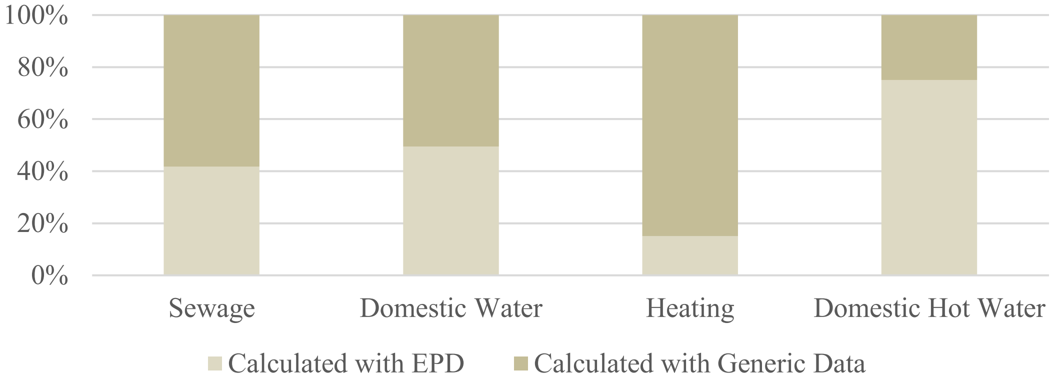

Figure 21: Climate data sources of Hedda's calculate plumbing components.

5.4. Analyzing the calculations in comparison to reference values

To establish the accuracy of the findings, the embodied carbon assessment was compared with a study led by Tove Malmqvist (Malmqvist et al., 2023), where reference values of the environmental impact of buildings and their infrastructure were determined. This comparison ensured the validity of the results by acting as a validation tool for the methods used in the study. Through this level of examination, any inconsistencies in the data could potentially be found and fixed, enhancing the research's credibility.

For an appropriate comparison, the reference values from Malmqvist and colleagues had to be converted, since they were originally given in kgCO2e/m² A_{temp}. The reference values for plumbing and ventilation within the category "schools" resulted in converted values of 11 and 24 kgCO2e/m² BTA, respectively, using a conversion factor of $\frac{1}{0,9}$ from BTA to A_{temp}, according to (Energimyndigheten, 2010) guidelines. An overall of 35 kgCO2e/m² BTA was produced as a result. The same conversion was done for the reference values within the "office category", which resulted in converted values of 11 and 22 kgCO2e/m² BTA for the plumbing and ventilation, respectively, with a total value of 33 kgCO2e/m² BTA.

A close alignment is seen when comparing the calculated results for kg CO2eq./m^2 with reference values (See Table 7). It's interesting to notice, nevertheless, that the computed values were marginally less than the reference values. This implies that although the method and analysis approach were solid, there can be minor differences or conflicts between the study's data sources or assumptions and the reference values. However, the consistency between the outcomes and the reference values offers assurance regarding the precision of the conclusions and the dependability of the analytical techniques.

Table 7: Calculations in comparison to the reference values (Malmqvist et al. 2023).

Building part	**Hedda gymnasium [kg CO2eq./$\mathrm{m}^2 BTA$]**	**Reference: Office [kg CO2eq./$\mathrm{m}^2 BTA$]**	**Reference: School [kg CO2eq./m^2BTA]**
Plumbing	*6*	*11*	*11*
Ventilation	*23*	*22*	*24*
Total	*29*	*33*	*35*

5.5. Hotspot analysis

The process of identifying regions or elements of a system that have a noticeably greater influence or concentration than others is known as a hotspot analysis. A hotspot analysis was used in this study to evaluate the embodied carbon emissions of several parts of the Hedda's ventilation, sanitary and heating systems. The ventilation group's duct system was found to have the most impact, accounting for 248 000 kg CO2 equiv., when the assessment data were analyzed based on Figure 22 below.

The duct system category has been designated as a priority area for improvement efforts based on the findings of the hotspot analysis. The purpose of this assessment is to address the significant climate impact that these specific components within the ducting category have. With the help of this analysis, resources can be allocated more wisely, and measures can be put into place in order to reduce the carbon footprint of the facility's building service systems.

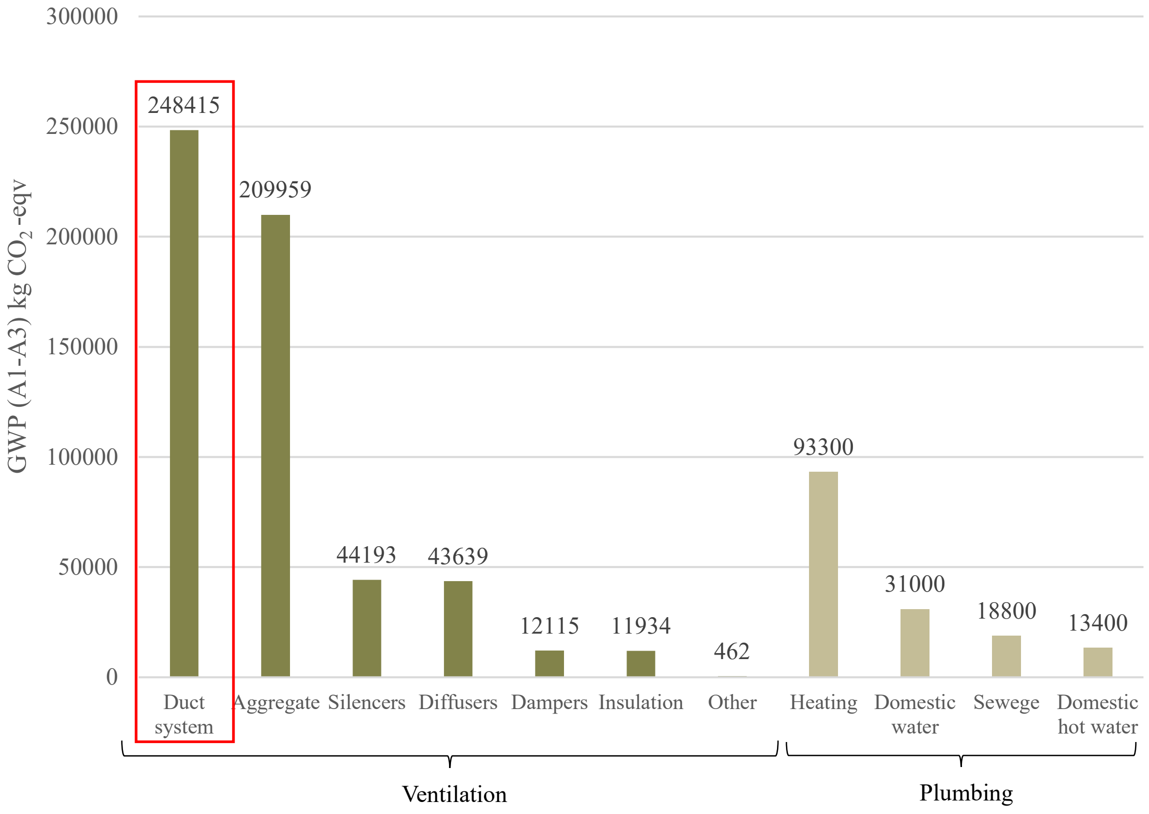

Figure 22: Hotspot analysis.

5.6. Analysis of emission reduction potential

This section is dedicated to investigating methods for reducing the embodied carbon emissions related to the category of duct systems (See Figure 22). The replacement of conventional stainless-steel components with recycled steel substitutes is one strategy being considered. In particular recycled stainless steel is highlighted. Compared to traditional materials, this material has substantial potential for decreasing environmental impacts, especially when it includes a composition with at least 75% recycled scrap steel.

This analysis aims to assess the possible emission reduction that may be achieved by using recycled steel instead of regular stainless steel for duct system components. The method used for assessing the environmental advantages of switching to more sustainable alternatives was by calculating the difference in embodied carbon emissions between the two material options.

The following graph will show the relative emissions profiles of recycled steel and conventional stainless steel, giving an idea of how much reduction in the carbon footprint can be achieved within the ventilation category.

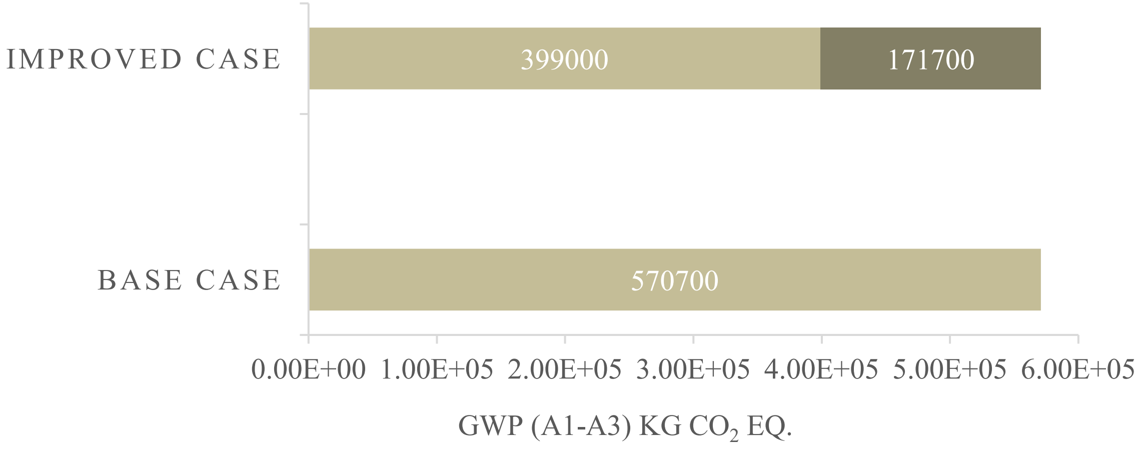

Figure 23: Hedda's ventilation climate impact reduction potential.

Reducing the overall embodied carbon emissions related to the ventilation system is made possible by putting the suggested improvement approach for the duct system into practice. Making the transition to recycled steel materials might result in a notable 171,700 kg CO_2 eq. decrease in carbon footprint. This reduction equates to a 30% reduction in the environmental impact, with the total carbon footprint of the investigated ventilation system coming in at 399,000 kg CO_2 eq.

This significant reduction highlights how effective sustainable material selections are when it comes to reducing the climate impact of building service systems. It also emphasizes how crucial it is to make calculated decisions when choosing materials with reduced embodied carbon content in order to support overall sustainability goals or targets.

6. Discussion

6.1. Discussion of the results

This study analyzed materials and components of MEP in Hedda gymnasium located in Lund, and their climate impact, specifically carbon emissions (GWP) during their manufacturing stage (A1-A3). The list of materials was provided by Assemblin, whereas EPDs and other environmental data about the products and materials were found on the manufacturer's websites and different EPD online databases (See the list of databases in the Appendix). To this date when this study was conducted, there is a lack of environmental data on electrical components, which made it impossible to conduct full LCA for electrical part.

Figure 23 below presents the calculated climate impacts and weights of the study. The ventilation section has the highest impact GWP = 23 kg CO_2 eq. / m^2, compared to the plumbing emissions GWP = 6 kg CO_2 eq. / m^2 and the electrical part which was not completed. Within the ventilation part, the duct system has the highest impact with GWP = 10 kg CO_2 eq. / m^2, followed by air handling units by GWP = 8 kg CO_2 eq. / m^2, which makes the most impact on this section. Whereas in the plumbing group, heating has the highest climate impact GWP = 4 kg CO_2 eq. / m^2 followed by DHW GWP = 2 kg CO_2 eq. and sever GWP = 1 kg CO_2 eq. Also, the weight of the materials has a similar ratio to their climate impact.

The ventilation section's total weighting is 10 kg / m^2, and when looking further, the duct system is the heaviest at 5 kg / m^2 followed by air handling units at 1 kg / m^2, and so on. The plumbing part contributes to the building with 2 kg / m^2, heating leads by weighting at 1 kg / m^2, followed by domestic water at 0.6 kg / m^2 and sewage system at 0.3 kg / m^2. Domestic hot water is the lightest by only 0.1 kg / m^2.

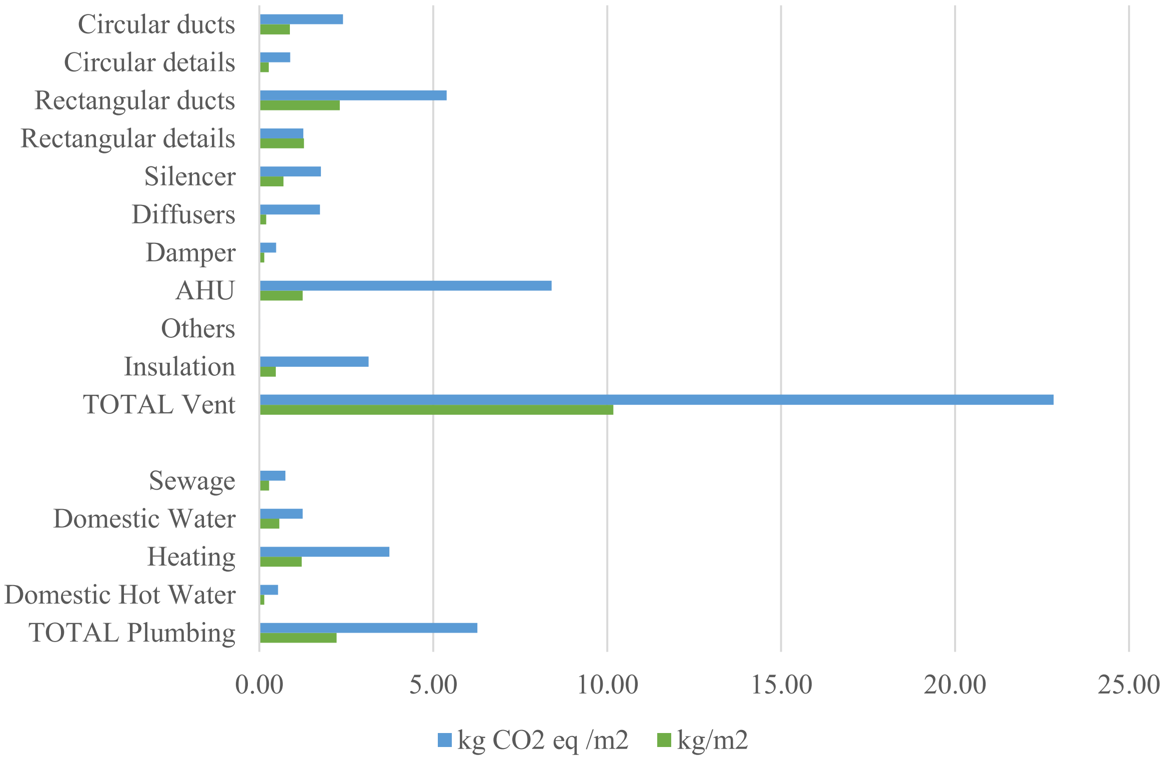

Figure 24: Calculated climate impacts and weights of the parts of the system.

Figure 24 below presents the ratio between the weights of system materials and their climate impacts. This is done by summing the weight of each section and its climate impact to a total of 100%. This provides a clear view of the efficiency of the system parts. Elements with high climate impact relative to their weight should be investigated, and innovative solutions should be proposed to decrease their impact.

The average ratio between the weights of system materials and their climate impacts for all components is approximately 30/70%, although it varies from section to section. According to the results, diffusers have the highest climate impact relative to their weight, followed by air handling units, among others. As an example, this could lead to proposing alternative solutions for these sections, which would result in lowering the overall embodied carbon footprint.

This approach of comparing the weight of component materials to their environmental impact provides a useful analytical foundation for identifying climate impact inefficiencies in MEP systems. Future research may use this technique to identify components with disproportionately high environmental impacts compared to their mass, driving targeted improvements and material replacements to minimize the overall carbon footprint of MEP systems.

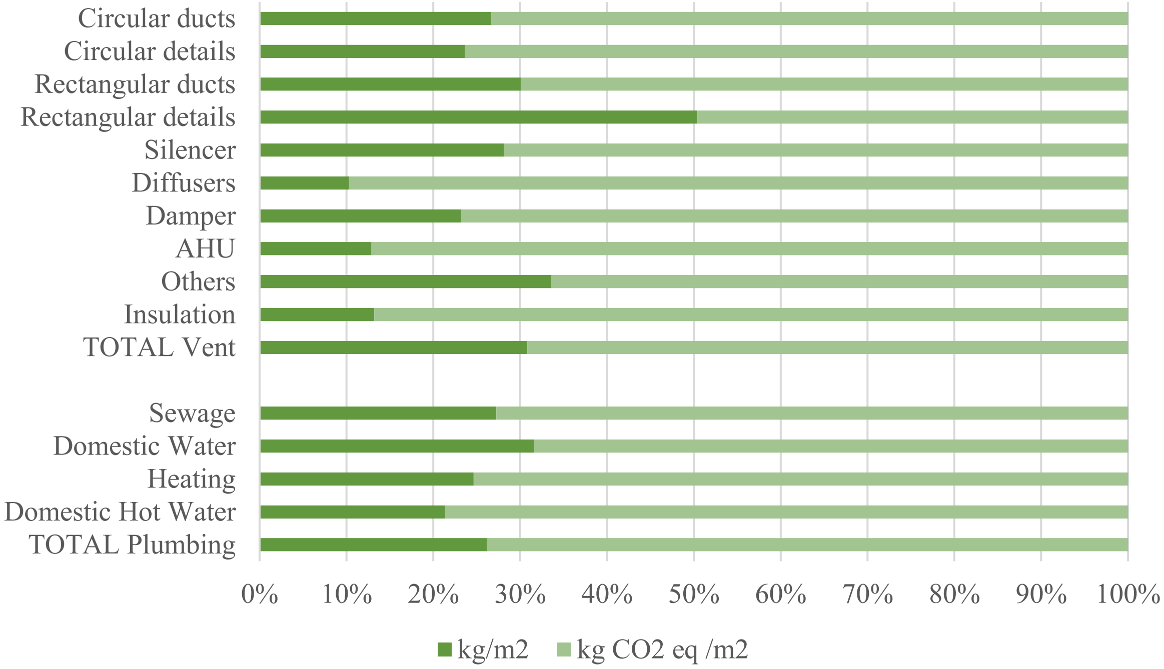

Figure 25: Weights of systems parts versus environmental impacts.

Because there is no specific threshold provided or established yet by Boverket for ventilation, electrical, and plumbing embodied carbon emissions, the results of this study were compared with similar results of other studies, and they are within the acceptable range of environmental impacts for similar systems and buildings. This will be covered more in detail in the following chapter.

However, according to Boverkets evaluations, all load-bearing structural elements, internal walls, and the climatic barrier should have less climate impact than 380 kg CO2e/m2 BTA for schools, within phases A1 through A5. This may be compared with Hedda Gymnasiums MEP system, where the calculated climate impact for phases A1–A3 were 29 kg CO2e/m² BTA. Furthermore, a 23 % reduction in the overall carbon footprint of plumbing and ventilation was achieved by employing recycled steel for the buildings duct system. Compared to Boverkets objectives, this reduction amounts to around 2 % of the building's overall carbon footprint.

6.2. Comparison to other studies

The Hedda Gymnasium research provides crucial insights into its embedded carbon emissions. Its results, which excluded the electrical system because of poor environmental data availability, provided a figure of 29 kg CO_2 eq./$m^2 BTA$ (23+6 kg CO_2 eq./$m^2 BTA$). These findings provide a fundamental understanding of the climate impacts of the gymnasium. The gymnasium's relative carbon footprint and its compatibility with other building projects are further defined through comparisons with similar research, also presented in the literature review chapter, see table 8 and figure 26.

In Calderon and colleagues study (Calderon et al., 2022), the overall calculated climatic effect (A1-A3) of the preschool in Gothenburg was 35 kg CO_2 eq./$m^2 BTA$. However, the electrical system was included in this number, which is not included in the Hedda Gymnasium estimates. The preschool's carbon footprint, excluding the electrical system, drops to 20 kg CO_2 eq./$m^2 BTA$, which is slightly less than Hedda Gymnasium's figure. Keeping in mind that the preschool project's explicit goal was to decrease embodied carbon, which makes this figure make sense.

Furthermore, two Swedish university buildings were the subject of a masters thesis from Chalmers University (Frendberg & Wiksten, 2023), which found that the "Umeå building" had a carbon footprint of 30 kg CO_2 eq./$m^2 BTA$ and the "Nya Konst building" had a carbon footprint of 31 kg CO_2 eq./$m^2 BTA$. Even though these numbers are slightly higher than the findings from our investigation, they are still within a comparable range.

Finally, two office buildings with different heating systems were the topic of Enebjörk and colleagues analysis in 2022 (Enebjörk et al., 2022). The estimated embodied carbon footprint of the example buildings “Office Building 1” and “Office Building 2” heating systems were 23 and 31 kg CO_2 eq./$m^2 BTA$, respectively, which is in good alignment with this study’s results.

Table 8: Summary of comparison with results from other studies.

Building	Climate impact (A1-A3)
Hedda Gymnasium	29 kg CO_2 eq. / m^2 BTA
Hoppet Preschool (Calderon et al., 2022)	35 kg CO_2 eq. / m^2 BTA
Umeå Building (Frendberg & Wiksten, 2023)	30 kg CO_2 eq. / m^2 BTA
Nya Konst (Frendberg & Wiksten, 2023)	31 kg CO_2 eq. / m^2 BTA
Office Building 1 (Enebjörk et al., 2022)	23 kg CO_2 eq. / m^2 BTA
Office Building 2 (Enebjörk et al., 2022)	31 kg CO_2 eq. / m^2 BTA

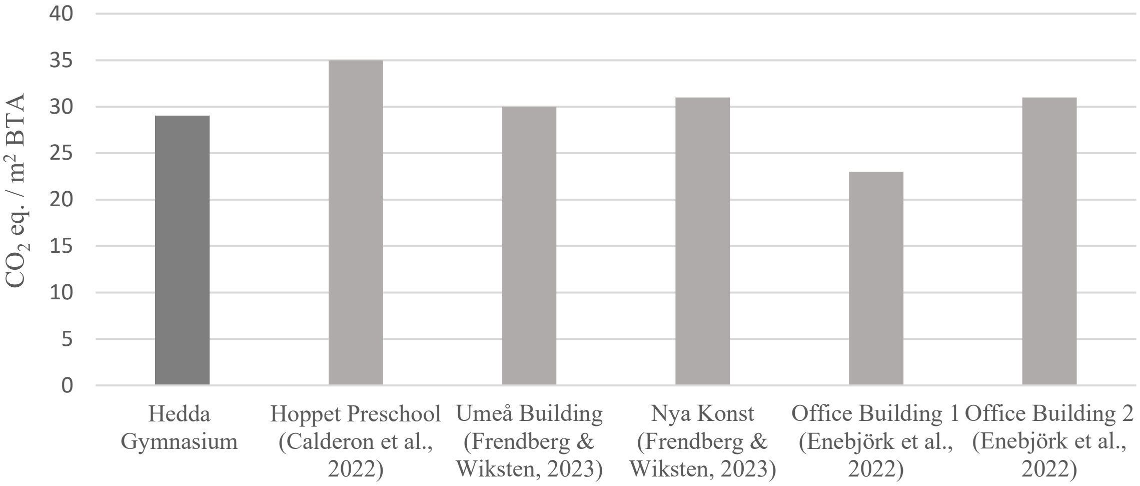

Figure 26: Visualization of comparison with results from other studies.

6.3. Challenges in data processing and data deficiencies

The paper has identified several obstacles in obtaining the data required to perform calculations and evaluate the present status of material data, generic data, and environmental product declarations (EPDs). Finding information on the weight and material composition of the goods stated in the bill of materials (BoM) has proven to be a significant challenge during this project. It has become clear that the climate impact calculations may be made much more efficient and quickly by including this data into the Building Information Modelling (BIM) system.

One additional noteworthy challenge was the lack of EPDs. About 65 percent of the calculated embodied carbon for Hedda Gymnasium was based on product-specific EPDs. A small percentage also included Building Product Declarations (BPDs) in combination with EPDs, although they were less accurate than EPDs that were specifically designed for the product or component. In these cases, the evaluation did not include the assembly of the product or the transportation of components to the product's manufacturer. Using generic data also led to less accuracy because this data often fails to capture the specific environmental impacts associated with individual products or components, instead offering average values that may not align with the actual materials used. Despite this inaccuracy, generic data were utilized due to the absence of EPDs. The accuracy and dependability of the calculations made are directly impacted by the selection of data sources. Specific data such as environmental product declarations (EPDs), provide a more realistic picture of a product's true environmental impact and provide a more exact basis for computations.

Moreover, the absence of data in the BoM lists created substantial challenges for the climate impact assessment. Among other important facts, these omissions included missing information on product model names and makers. Because of this, it took more time and effort to make assumptions when speculating on producers. Such information would have accelerated the procedure and improved accuracy if it had been included for every product or component in the BoM lists. Complete Bill of Materials (BoM) lists are essential for the building industry because incomplete information about product model names and manufacturers can seriously impair the precision and effectiveness of climate impact evaluations. Quicker and more accurate assessments of environmental footprints are made possible by easily accessible information, and these assessments are crucial for making well-informed judgments on sustainable construction methods.

7. Conclusion

Among ventilation and plumbing installations within Hedda’s building, ventilation, especially duct systems and AHUs (air handling units), has the highest climate impact compared to other parts of these systems.

Both this study and the literature review show that selecting materials within MEP systems plays a significant role in determining the carbon footprint. Aluminum, copper, steel, and cast iron are mostly used in these systems because of their specific properties, but their manufacturing stage also has a high environmental impact. This conclusion is confirmed by embodied carbon calculations and Environmental Product Declarations (EPDs) that document the substantial energy use and greenhouse gas emissions during the production of these metals. Further, comparative analyses in the literature highlight that these materials, when compared to alternatives, have significantly higher climate impact due to their intensive manufacturing processes.

Currently, there is a shortage of environmental data on electrical products, making it difficult to perform a thorough LCA (Life Cycle Assessment) on this portion of the system. This study could potentially motivate electrical component manufacturers to begin producing EPDs for their products. Encouraging the production of Environmental Product Declarations (EPDs) for electrical components is essential for enhancing transparency and enabling more accurate embodied carbon calculations. Without progress in this area, manufacturers may face regulatory penalties, reputational damage, and missed opportunities in markets prioritizing sustainability, potentially hindering the overall goal of reducing environmental impact in the industry.

Using hotspot analysis made it possible to identify parts within ventilation, such as the duct system, with the highest climate impacts. The study proposed using recycled steel material for this section, which made it possible to reduce the ventilation's carbon footprint by 30%, or about 23% of the total ventilation and plumbing carbon footprint.

Comparing the results of the study to other similar studies provided context for the results. By considering the scope and nature of the building, the study results fall within acceptable ranges.

Future research should focus on improving data accessibility and quality or accurate estimation techniques to enable more thorough environmental evaluations. The study demonstrated data processing issues and gaps in accessible environmental data, underlining the need for better data gathering and sharing strategies.

In summary, the study emphasizes the need to implement environmentally friendly approaches to building construction. From selecting materials to system design, data-driven choices may lower the climate impact of MEP systems, helping accomplish all sustainability goals.

Furthermore, when comparing our findings to those from a full LCA, it is crucial to include the operational phase, particularly the efficiency of Air Handling and Climate (AHC) systems. While this research focuses mainly on the climate impacts of the construction of MEP, a full LCA would assess the long-term emissions and energy consumption connected to the operation of ventilation and plumbing systems. Efficient AHC systems can help to minimize a building's operational carbon footprint over time. The total climate impact of a building may be reduced further by adding advanced, energy-efficient technology into AHUs and other components.

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9. Appendix

9.1. Generative Artificial Intelligence

1) I used a Generative AI tool (e.g. ChatGPT or similar) in my report --> YES.

2) I used a GAI tool as language editor (i.e. to correct grammar mistakes, etc.) --> YES.

3) I used GAI to retrieve information --> NO.

4) I used GAI to get help in writing code --> NO.

5) I used GAI for translations --> NO.

6) I used GAI to generate graphs/images --> NO.

7) I used GAI to help structuring my content --> NO.

The use of Generative Artificial Intelligence (GAI) techniques in this thesis has been thoughtfully carried out with strict regard to the academic standards mandated by Lund University, with the specific goal of proofreading and grammatical validation. By utilizing advanced artificial intelligence algorithms and leveraging natural language processing, these instruments have been valuable in closely examining the textual material, guaranteeing accuracy and consistency. This methodological approach is indicative of the university's steadfast dedication to upholding the highest standards of intellectual honesty.

9.2. BoM-list of building service systems

Table 9 Number of elements in the MEP systems (Calculated from BoM lists provided by Assemblin) and their climate impact calculation.

System	**Number of items**	**Unit**	**Impact calculated**
Ventilation	6798	Pcs	100%
Plumbing	46397	Pcs	100%
Electrical	222205	Pcs	28%
	252654	m	61%

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