Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Civil and Environmental Engineering

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Embodied Carbon of Technical Installations in a Norwegian Office and Teaching Building

An LCA-based study of the Ocean Space Center

Master's thesis in Energy and Environmental Engineering
Supervisor: Ottar Michelsen
Co-supervisor: Christofer Skaar

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Preface

This is a master thesis in the 5-year Master of Science degree at the Norwegian University of Science and Technology, Department of Industrial Ecology, at the study program Energy and Environmental Engineering.

Several people have been essential for the successful completion of this thesis. First of all, I would like to thank my supervisors, Ottar Michelsen and Christofer Skaar, for always stearing me in the right direction and pushing me to be goal-oriented with my work. Also, thanks to Mads Mysen, for providing an interesting topic for the thesis, allowing me to develop the study based on my interests, and providing valuable insight into relevant topics and helpful discussions concerning the subjects of the thesis.

I would like to thank Karin Anton, the rest of the team in the ZEN case working group, for providing me with with BIM files, project related documents and sharing their work in building the life cycle inventory. Also thanks to everyone at Statsbygg, who gladly answered any questions concerning the Ocean Space Center.

Abstract

Greenhouse gas emissions from energy use during a building's lifetime have been studied in detail, and significant improvements in energy efficiency have been made in recent years. The reduction of CO_2 emissions related to energy use of buildings has subsequently increased the relative importance of embodied carbon in building materials, creating a global shift towards embodied carbon reduction in the building sector. The embodied impacts of technical installations are poorly documented, but the documentation available indicates the emissions make up a significant proportion of the buildings' total emissions.

The main goal of this thesis is to assess the embodied environmental impact of technical installations through a literature review and a Life Cycle Assessment (LCA) case study of an office building, the Ocean Space Center. The thesis also aims to evaluate Environmental Product Declarations (EPD) as a tool to reduce greenhouse gas emissions and improve environmental properties. Building Information Models (BIM) and planning documents are used to build the Life Cycle Inventory, and calculations are for both generic and EPD data.

Findings from the literature review indicate that the material part of technical installations is inadequately addressed in most studies, and there is a need for better resolution in terms of components, material composition, and dimension. While there is large variation between studies, the share of emissions attributed to the material content of technical installations is considerably larger in recent studies with more detailed inventories.

The results show that the technical installations in the assessed office building in OSC contribute to 33-46% of total embodied emissions. The ventilation system is shown to have the most significant impact, with ventilation ducts, Variable Air Volume (VAV) supply air units, and air handling units contributing to the largest share. Calculations made with EPD data show impact reductions of 41% compared to generic, though there is considerable uncertainty related to these results. Nevertheless, use of Environmental Product Declarations are found to improve the embodied impacts of technical installations profoundly.

Sammendrag

Klimagassutslipp fra energibruk i bygninger er betydelige, men store forbedringer i energieffektivitet har blitt gjort de siste årene. Som en konsekvens av redusert CO_2 utslipp grunnet lavere energibruk, har den relative betydningen av indirekte utslipp økt og skapt økt fokus på redusering av indirekte karbon utslipp fra materialer i byggebransjen. Indirekte klimagass utslipp fra tekniske installasjoner er dårlig dokumentert, men den tilgjengelige dokumentasjonen indikerer at de utgjør en betydelig andel av bygningens totale utslipp.

Hovedmålet med denne oppgaven er å vurdere den indirekte miljøpåvirkningen av tekniske installasjoner gjennom et litteratur studie samt en livssyklusanalyse (LCA) case study av en kontorbygning i Ocean Space Center (OSC). Oppgaven har også som mål å evaluere miljødeklarasjoner (EPD) som et virkemiddel for å redusere klimagassutslipp og forbedre miljøegenskaper. Bygningsinformasjonsmodeller (BIM) og funksjonsbeskrivelser er benyttet til å lage livssyklusinventariet, og LCA beregninger er gjort for både generiske og EPD-data.

Funn fra litteraturstudiet indikerer at den de fleste studier ikke adresserer den materielle delen av tekniske installasjoner tilstrekkelig, og det er behov for bedre oppløsning mht. komponenter, materialsammensetning og dimensjoner. Andelen utslipp som tilskrives materialinnholdet i tekniske installasjoner varierer betydelig mellom studiene. Imidlertid er de vist å ha en mer betydelig påvirkning nyere studiene med mer detaljerte inventarer.

Resultatene viser at de tekniske installasjonene i det vurderte kontorbygget i OSC bidrar til 33-46 % av de totale indirekte utslippene. Ventilasjonssystemet er vist å ha størst innvirkning, der ventilasjonskanaler, VAV-tilluftsenheter og aggregater bidrar til den største andelen. Beregninger gjort med EPD-data gir en reduksjon av utslipp på 41 % sammenlignet med generisk, selv om det er betydelig usikkerhet knyttet til disse resultatene. Bruk av miljøproduktdeklarasjoner i klimagassregnskap viser allikevel at de indirekte utslippene fra tekniske installasjoner blir redusert i stor grad.

Contents

List of Figures

List of Tables

Acronyms

AHU Air Handling Unit. 28, 31

BIM Building Information Model. vii, 8, 25

BREEAM Building Research Establishment Environmental Assessment Method. 7

EPD Environmental Product Declarations. 6

GFA Gross Floor Area. ix, 24, 25

GHG Green House Gas. 1

HFA Heated Floor Area. ix, 24

IFC Industry Foundation Classes. 26

LCA Life Cycle Assessment. 1

LCI Life Cycle Inventory. 8, 25

LCIA Life Cycle Impact Assessment. 8

LEED Leadership in Energy and Environmental Design. 7

OSC the Ocean Space Center. 25–27

VAV Variable Air Volume. 28

1 Introduction

Global warming caused by greenhouse gas emissions is arguable the largest treat currently facing our civilization. The most important greenhouse gas, as measured by total impact on climate, is carbon dioxide (CO2), a byproduct of burning fossil fuels. Consequently, curbing CO2 emission is the main focus in the effort to slow global warming. The building sector is the second-largest CO_2 emitter and accounted for 36% of final energy use and 39% of energy and process-related CO_2 emissions(IEA, 2019). Most of the energy use from buildings is contributed to the use-phase, however, the IEA found in their 2019 status report for buildings and construction that 11% of energy and process-related CO_2 emissions are the result of the production of building materials (IEA, 2019).

The need for a more detailed understanding of CO2 emissions associated with buildings is broadly recognized. Life Cycle Assessment (LCA) is a science-based technique used to assess the environmental aspects and potential impacts associated with a product overall, or for select stages of the life cycle. The importance of revealing the environmental impact of buildings and having environmental transparency is broadly recognized. A tool such as LCA can be used to identify the possible areas or stages in a product's lifecycle with the greatest environmental impact in order to achieve more sustainable building practices.

In recent years there has been major progress in lowering the energy demand of buildings. As new solutions and technology for building structure, energy efficiency, and energy production contribute to lowering the green house gas (GHG) emissions of the operational phase, the relative importance of embodied emissions increases. Embodied emissions refer to emissions from the production, transportation, construction of building materials for use in different life cycle stages. In depth analysis have revealed that the average share of embodied GHG emissions from buildings following the current energy performance regulations is approximately 20-25% of life cycle GHG emissions (Röck et al., 2020). This figure escalates to 45-50% for highly energy-efficient buildings and surpasses 90% in extreme cases. These developments underline the need to assess the embodied carbon of the whole building.

Reducing the energy use in buildings has among other things required more efficient solutions for energy supply and improved concepts for ventilation. In order to satisfy requirements for low energy use and indoor air quality imposed by new regulations, modern energy-efficient ventilation is practically mandatory in new buildings. However, these changes also leads to increased complexity of technical installations in buildings. As such, there is often a trade-off between the decrease in energy use in buildings and the increased embodied emissions in energy-efficient buildings. While there has been an increased focus on embodied emissions from buildings in recent years, most studies have a tendency to focus on the main construction materials, in turn falling short on the heating, ventilation, and air conditioning (HVAC) (Ibn-Mohammed et al., 2013). Very few studies include detailed HVAC system calculations. Thus, there is a need for better resolution in terms of components, material composition, dimensions, and lifetime (Bergsdal, 2020).

While embodied GHG from technical installations generally are poorly documented, available data indicates that the emissions associated their manufacturing and installment make up a significant proportion of the buildings' total lifetime emissions (Bergsdal, 2020; RICS, 2017; Borg, 2016; Wiik et al., 2018) Building Information Model (BIM) can be utilized to extract information about the building, and thus give better resolution of components and dimensions.

In this thesis, the embodied carbon emissions from technical installations are investigated through literature review and a case study of the Oscean Space Center. The Ocean Space Center (OSC), which is still in early planning phases, will be one of the world's most advanced facilities for ocean research and education. The environmental ambition for the construction project is high, and it is planned to be an almost zero energy building with PV-panels, heat recovery and energy-efficient equipment. The embodied impact of the ventilation, heating and comfort cooling systems, in addition to some of the electrical installations in one of the office buildings in the OSC center are assessed through the use of BIM models and LCA. The goal and scope of the study is defined to answer the following research questions:

- What is the current status in literature on life cycle assessment information on HVAC and other technical installations in buildings, and the contribution of embodied emissions in the material content of these installations?
- What are the embodied environmental impacts of the technical installations in wing A of the Ocean Space Center in regards to climate change?
- How can the introduction of environmental product declarations reduce greenhouse gas emissions and improve the environmental properties of technical installations in buildings?

2 Background

This section presents the background of the study. First, the development of ventilation systems and technical installations are outlined, followed by the importance of environmental transparency and the role of EPDs in achieving it. Then green building certifications and building information models and their connection to LCA is shown. Finally, an introduction to LCA methodology is given.

2.1 The Increased complexity of technical installations in buildings

In recent years new regulations have had a strong influence on building practices regarding ventilation and other technical installations in Norway and other European countries. The implementation of the Energy Performance Building Directive (EPBD) enforced stricter requirements for indoor air quality and low energy use (Litiu, 2012). Norwegian building standard TEK 17 also proposes to avoid unnecessary cooling in new buildings, which has led to local water-borne cooling largely being replaced with more efficient ventilation cooling (*Regulations on technical requirements for building works* 2017). As a result, ventilation systems may provide larger airflows than the minimum requirements in many buildings.

These developments have in practice made energy efficient installations for ventilation, heat and cooling mandatory in new buildings. Figure 1, shows the evolution of ventilation systems in several countries in the EU over the past decades. In Norwegian homes, the category “other”, mainly consists of mechanical ventilation, meaning ventilation is fan driven (Litiu, 2012).

The general outcome of this evolution is more efficient ventilation systems that supply high airflows, while preserving energy. However, these larger and more complex ventilation systems also increase material use. While these developments have greatly reduced the energy-use and health risks of modern buildings, the manufacture of larger and more complex technical installations entails increased embodied emissions and the resulting environmental impacts are at this point not well documented. Thus, a more detailed understanding of the environmental impact of such installations is needed.

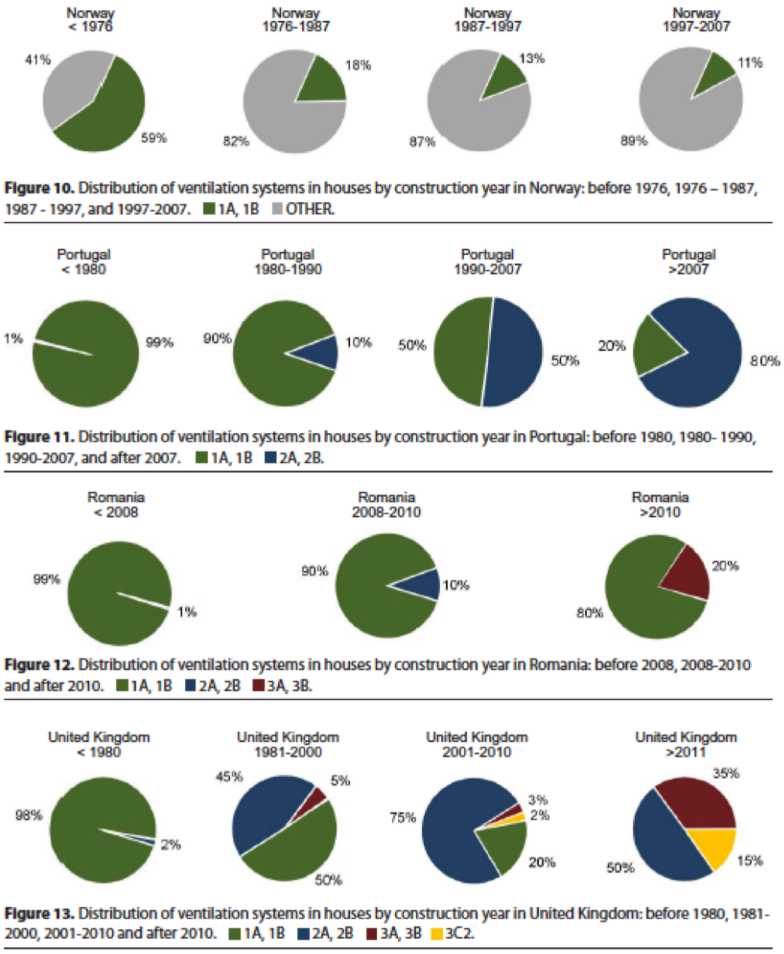


Figure 1: 1A, 1B - natural ventilation, 2A, 2B - natural assisted with fans, 3A,3B - mechanical ventilation, 3C2 - mechanical extract and supply ventilation without heat recovery (Litiu, 2012)

2.2 The Importance of Environmental Product Transparency

Increased complexity of technical installations, and potentially increased embodied impacts as a result, in turn increases the need for information and transparency from manufacturers. In a competitive marketplace, claims of product superiority can tip the scales in one manufacturer's favor. This also includes claims of environmental superiority. As the threat of global warming has gained more attention in media and politics, greenwashing, a form of misleading marketing in which a product or business is presented as more environmentally friendly than it actually is, is becoming a larger issue also in the building industry (Schoeman and Gunter, 2018). As there are costs related to carbon emissions (*Meld. St. 21* 2012), contractors are interested in buying and selling products that use less energy and thus are less likely to increase in cost if a higher price on carbon is introduced in the market. However, without transparency it is difficult to know which products actually have better environmental performance. One way to ensure transparency is through Environmental Product Declarations (EPDs). This way organizations can better understand the environmental impacts associated with the products they purchase and thereby also reduce potential economic risks.

2.2.1 Environmental Labels

There are many different environmental labels that all aim to persuade customers to believe their product is enviornmentally superior. However, how do consumers know that the labels being used in today's marketplace are accurate and trustworthy? To adress these issues, ISO (International Organization for Standardization) has developed a series of environmental labeling standards (ISO 14020s).

Environmental labels can be categorized into 3 broad categories:

> Type 1 Eco-label – indicates that a product has met a specific environmental performance (most frequently seen on consumer products). However, these environmental performances can be defined by the company themselves, and are not necesseceraly held to any defined standard.
>
> Type 2 Eco-label – claims made for goods and services by the producer, and are referred to as self-declared labels (no procedures for external groups to verify that Type 2 label claims are accurate)
>
> Type 3 Environmental Product Declarations (EPD) - EPDss are science-based environmental labels indicating the environmental impact of a product throughout its lifecycle. EPDs are the results of life cycle assessment studies that quantify environmental attributes based and are based on a given set of rules for product category to which they belong. The EPDs and the LCAs that contribute to the declarations are third-party verified. Consumers can then use EPDs to compare the environmental impacts of products.

2.2.2 Product Category Rules

In order to develop an EPD for a specific product, there first needs to exist a Product Category Rule (PCR) for the category that specific product belongs to. PCRs are specific rules, requirements and guidelines for developing EPDs for a particular product category. Product categories are often based on similar components or products with similar functions. They aim to standardize the way an LCA for a particular product type should be performed and the way information is communicated in the EPD resulting from the LCA. Essentially, PCRs are the standard for how to conduct a lifecycle assessment and prepare an environmental product declaration for a product category. The following requirements for the life cycle assessment for a product category are defined by the PCR:

- The functional unit (quantifies the function or perfomance recuirements of the product or system)
- scope and boundaries, this includes the life cycle stages that must be covered
- which environmental impacts are to be measured
- data quality requirements (percision, completeness, representativeness, consistency and reproducibility)

The goal of the PCR is to include the life cycle stages and impact categories that are of significant environmental effects for a given product type, to make sure that these are measured and subsequently communicated in the EPD. Arguably, the most important role of the PCR is to ensure that the various EPDs for similar products are comparable. PCRs are generally developed by the industry of which that product category belongs to in cooperation with program operators. Program operators are independent agencies whose role is to conduct, administer, and supervise the development of PCRs and EPDs. Program operators are also resposible for keeping a register of existing PCR.

2.2.3 Environmental Product Declarations

Environmental Product Declarations is one of the most reliable ways for buyers to compare the environmental performance of products and make informed decisions about what choices to make. Once a PCR exists for a given product type, environmental product declarations can be developed by manufacturers with the supervision of program operators, through the following development process:

1. Find an appropriate PCR in program operator register / develop one with a program operator if one doesn't exist
    - This dictates the scope of the Lifecycle stages, Environmental impacts and Functional unit
2. Conduct LCA
    - This quantifies the environmental impact of a product through its lifecycle, as defined by the PCR
3. Develop EPD
    - Reporting of LCA data in accordance with PCR
4. Verify EPD
    - EPD and LCAre submitted to an independent body approved by the program operator to verify
    - Verified against the PCR and ISO 14025
5. Verified EPD is posted by a Program Operator

There are several reasons to develop EPDs. As they are mostly used in business-to-business applications where the buyer wants to know the environmental impacts of the product they are purchasing, the buyer can potentially influence the development of EPDs by setting requirements of the manufacturers. This way manufacturers will need to develop EPDs to stay in line with expectations in the market. Another reason for manufacturers to develop EPDs is to increase transparency of environmental impacts of products to buyers in their supply chain and diffirentiate themselves from competitors. Lastly, developing an EPD allows you to identify hotspots (areas of high environmental impact) in the production process, as they are not always intuitive. Manufacturers can then use the information revealed by the EPD to make process improvements that help the environment and may also save them money.

2.3 Green Building Certificates

Increased focus on sustainability in building design has led to the creation of several green certification schemes. The goal is to increase the awareness regarding different energy and heating solutions, as well as the choice of materials. The certifications also serve as a guidance tool for construction, comparison of buildings, and documentation of strategies and solutions implemented in the building. Many landlords of office spaces and real estate agents highlight such certifications as a competitive advantage as it may align with the environmental strategies of companies or the personal preferences and interests of tenants or buyers.

Examples of green certifications are the Leadership in Energy and Environmental Design (LEED) in the U.S., and the Building Research Establishment Environmental Assessment method (BREEAM) in Europe. In each of the certifications the environmental performance of a building is split into different issue categories, and assessment credits are aggregated for each category, weighted and finally a single score is given. Issue categories include, energy use, transport, water, materials, health and wellbeing, pollution, land use and ecology. LEED certifications also give credits for including a certain amount of materials and components with Environmental Product Declarations. As LCA methodology has the potential to aid early stage decision-making in construction projects regarding energy and environmental factors, BREEAM and LEED certifications can easily benefit from life cycle assessment. The assessment of these certifications start already in the design stage of the building, and it is therefore essential to apply methods that allow you to easily asses the environmental performance and make informed decisions in the early project stages.

2.4 Integrating BIM and LCA in Sustainable Building Design

Building Information Model or BIM is a powerful tool for providing detailed information about building components. Individual building objects such as wall structures, windows and ventilation components are modeled, and data on their dimension, material composition and cost ect. are collected in BIM databases. BIM software like Revit allows for data export to perform cost, energy, or environmental assessments.

There is currently an ISO standard under development that covers the principles and requirements to enable environmental and technical data provided in EPDs for construction products and services, construction elements and integrated technical systems to be used in BIM to assist in the assessment of the environmental performance of the construction works over its life cycle (Standard, 2021) Figure 2 shows the proposed workflow in the standard and the relationship between data, data sheets, BIM and LCA at the building level.

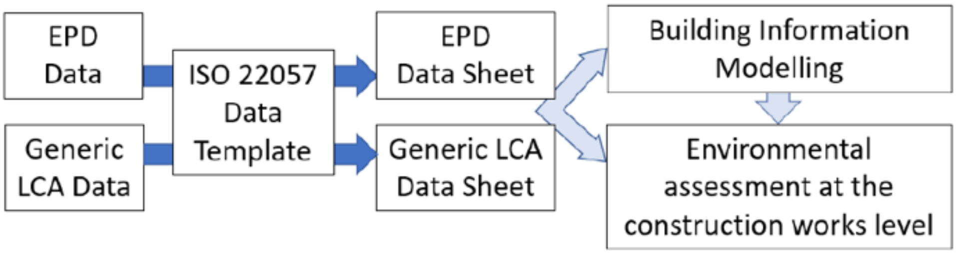


Figure 2: Proposed relationship between Data, Data templates, Data sheets, BIM and Environmental assessment at the construction works level (Standard, 2021)

2.5 LCA as a Tool for Analysing the Environmental Impact of Buildings

Life Cycle Assessment (LCA) is a method for assessing the environmental impact of a product or a building throughout its life cycle, from raw material extraction, through production and use, to end-of-life disposal of the product, as well as all transportation occurring in these phases. All use of materials, energy and services have to be included when conducting an LCA. LCA is an important tool for identifying hotspots - the areas or stages in a product's lifecycle with the greatest environmental impact. Hotspots are not always obvious and are important to identify as they are the logical place to start in order to improve the environmental performance of a product or system.

An LCA study consists of four phases; Goal and Scope, Life Cycle Assessment, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation. The method and rules for conducting an LCA assessing the GHG emissions for buildings are given by NS 3720 "Method for greenhouse gas calculations for buildings". NS 3720 is based on the widely-adopted European standard EN 15978 "Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method", but the Norwegian standard is significantly more specific in relation to what must be included in the calculations to make it possible to compare different solutions. Furthermore, the Norwegian standard provides the opportunity for partial calculations, i.e. one can "just" make an assessment of the project's location, consequences of different material choices, energy solutions, and the like. In addition, the standard specifies how comprehensive greenhouse gas calculations are to be performed, and different variants of the scope of such comprehensive calculations.

2.5.1 Goal and Scope

This is the defining phase of the study, and the goal of the LCA should inform the methodology to be used. At this phase, the purpose of the assessment is determined and presented, and the system boundaries are set. An example of a goal might be to compare two products or systems that serve the same purpose, in order to identify the alternative with the smallest environmental footprint. Another goal could be to identify hotspots in order to improve the environmental performance of a product or system.

The system boundaries define the cut-off criteria and the level of detail of the system is to be studied. Cut-off criteria must be consistent with the goal of the study, and it is important that decisions to exclude life cycle stages, processes, or data are clearly specified and justified.

Also, the functional unit is decided in this phase. The functional unit indicates the performance of a product in relation to specific user requirements and should reflect the specific function of the product or system that is to be analyzed in the assessment. The functional unit serves as a reference to which inputs and outputs are normalized and characterizes the system. The functional unit must be clearly defined and measurable.

The procedure for allocation should also be decided in this phase. Allocation is the distribution of input factors to output factors from a unit process to the product system being investigated. Allocation is required when a unit process in the life cycle of a product has more than one product or raw material, and which is part of another life cycle. This means that it will not be correct to allocate all environmental impacts from the unit process to only one of the products.

An LCA study only examines a certain number of environmental impact categories. Therefore, even if LCA is defined as holistic, it is still limited to the specific environmental stressors described in the scope of the study. Lastly, in this phase one decides the impact category, time horizons of impacts, category indicators, and characterization models that are to be included in the study.

2.5.2 Life Cycle Inventory

Once the goal and scope of the study have been defined, the life cycle inventory phase of the LCA is ready to be conducted. In this is the step where one quantifies all material and energy flows in and out of the product or system life cycle. It includes data collection and calculation procedures to quantify a product system's current input and output factors. The goal of the life cycle inventory or LCI is to quantify all energy and raw material needs, emissions to air/water, waste, and other emissions for each individual process in a process system.

The LCI results in a list of all occurring stressors associated with the life cycle of the functional unit, which is then further analyzed in the LCA phase.

2.5.3 Life Cycle Impact Assessment

In this phase, the stressors found in the LCI are translated to environmental impacts. The LCA is divided into four parts:

- Selection of impact categories and characterization models
- Classification
- Characterization
- Normalization, weighting and grouping (optional)

2.5.4 Interpretation

In this phase, one analyze results, draw conclusions, describe limitations and make recommendations. It is important that the purpose and scope of the study are taken into account here. This is necessary for the interpretation to provide value for later decision-making. I.e. if data gaps in the life cycle inventory prove to be significantly affect the study, it may be appropriate to repeat the LCA calculations to fill in the most important data gaps.

3 Methods

In this section, the methodology used to answer each of the research questions posed in section 1 introduction and the data flow between each method is outlined. First, an overview of the used methods is presented. Next, the particular methods used to answer each research question are presented in more detail, starting with the literature review. Finally, the methodology of the LCA is presented, starting with choices for goal and scope, then Life Cycle Inventory and Life Cycle Impact Assessment, and finally uncertainty of the study.

3.1 Methodology Overview

In order to answer the research questions outlined in section 1, different methodologies have been used. Figure 3 shows which methods are used to adress which question, and the information flow between the different work phases. Why the chosen methods are considered appropriate, is further elaborated in the following subsections.

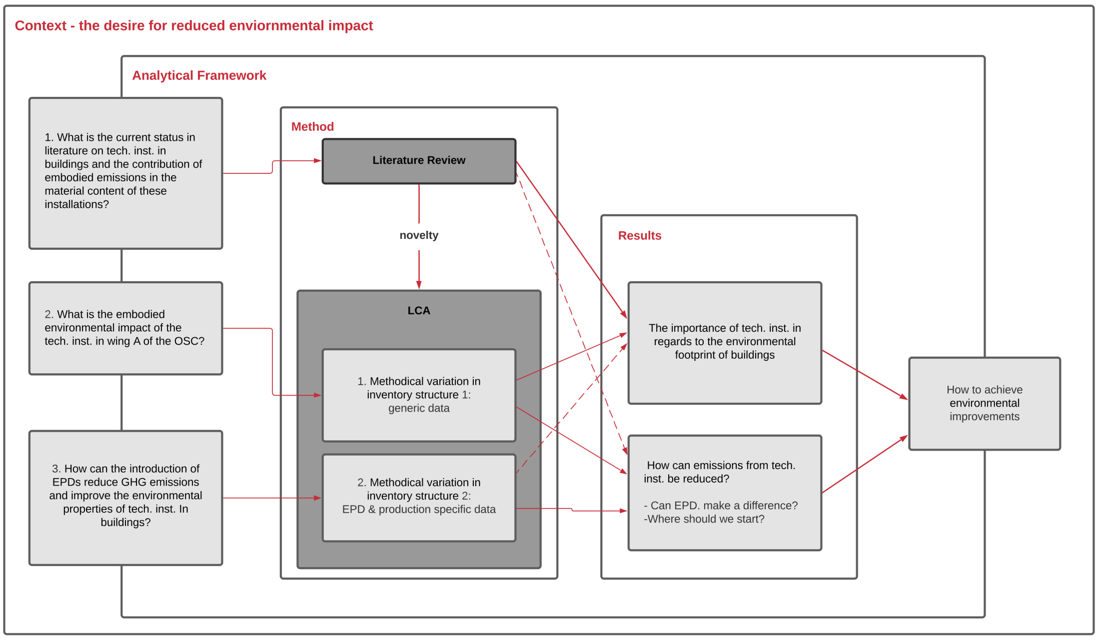


Figure 3: Context and structure of thesis

3.2 Literature Review

To identify the current knowledge on embodied emissions from technical installations in buildings, a literature review has been conducted. Relevant literature has been identified through literature and publication portals such as Google Scholar, ScienceDirect, SpringerLink, etc., by using search terms including LCA, embodied carbon, technical installations, HVAC, buildings, environmental analysis, electrical installations, MEP and more. The same publications appear across several portals, and the list of relevant literature is not very extensive.

Relevant articles are identified through reading abstracts, introductions and results. The criteria for which articles are considered relevant articles are that they use LCA to assess the environmental impacts of buildings and/or technical installations of some sort and assess the embodied impact of those technical installations. The relevant articles are sumarized and analysed to find parallels between varying results and the scope, assumptions, inventory and data quality in the studies. The following elements and their effect on the LCIA results are identified and discussed:

- Life Cycle Inventory
- Operational emissions and electricity mix
- The extent to which technical installations are included
- Environmental Impact Categories.

This methodology was chosen as it was found to be effective for analyzing which aspects are essential when assessing emissions from technical installations in buildings, as well as outlining the structure and novelty of further research in this thesis.

3.3 Life Cycle Assessment

To answer the second and third research questions, LCA is used to provide objective and science-based information about the embodied emissions from technical installations and how EPDs can potentially improve their environmental properties. The LCA method is based on the Norwegian Standard ‘NS 3720:2018 - Method for greenhouse gas calculations for buildings’ (2018).

3.3.1 Goal and Scope

The goal of the main LCA is to estimate the environmental impact from the embodied emissions in the technical installations in wing A of the Ocean Space Center. This is achieved through a life cycle assessment of the technical installations using the automated life cycle assessment software, OneClick LCA version Norge NS 3720, and their databases. The primary LCA model is calculated using generic data.

The second goal of the LCA is to determine whether the introduction of environmental product declarations can reduce the environmental impact of technical installations. To achieve this, a second analysis in OneClick LCA is performed with a different methodical inventory structure, using as much EPD and product-specific data as possible.

The scope of this study is a cradle-to-grave analysis of the embodied emissions from technical installations. The embodied carbon in a building consists of all the GHG emissions associated with the building construction, including those that arise from extracting raw materials, transporting and manufacturing components, and installing building components on-site, as well as the operational and end-of-life emissions associated with those materials.

Functional Unit
The technical installations in a building are numerous and serve several functions. To

Table 1: The different stages of a buildings life cycle as given in ('NS 3720:2018 - Method for greenhouse gas calculations for buildings' 2018)

Production stage	**Construction process stage**	**Use stage**	**End-of-Life Stage**
A1: Raw Materials Supply	A4: Construction - Installation process	B1: Use	C1: Deconstruction, demolition
A2: Transport	A5: Transport	B2: Maintenance	C2: Transport
A3: Production		B3: Repair	C3: Waste processing
		B4: Replacement	C4: Disposal
		B5: Refurbishment	
		B6: Operational energy use	
		B8: Transport in operation	

encompass all the functions of the technical installations, the functional unit is set to be $1m^2$ of heated floor area (BRA) over an estimated lifetime for the building of 60 years, which complies with the current Norwegian building regulations.

System Boundary

The system boundary of this study is determined by the goal and scope and is based on the modular approach described in standard NS 3720:2018. The life cycle stages included are all modules from the production stage, construction process stage, end-of-life stage, and module B4 from the use stage. All stages and modules in a building's life cycle, as given in NS 3720:2018 are shown in Table 1. The technical installations included in the system boundary are heating, cooling, ventilation, and electrical installations. The precision of the study is only as good as the inventory data provided, although efforts are made to fill the data gaps.

Environmental Impact Category

The only environmental impact category included in this study is global warming potential (GWP). The only mandatory impact categories in NS 3720 are GWP, Biogenic carbon storage, and Greenhouse gas emissions (LULUC). The latter two are not relevant for this study with the amount and quality of data available, and therefore only GWP is included.

3.3.2 Life Cycle Inventory

In this stage, the material and energy use for each of the phases is calculated. First, an inventory of all technical components included in the system boundaries was mapped, along with resulting material quantities and component lifetimes. As required by NS 3720, all product and material quantities are classified and coded in accordance with the subdivision in NS 3451 *Table of building elements.* OneClick LCA has a calculation database containing generic materials and processes and nearly all Norwegian and European EPDs. The energy use and associated emissions are calculated accounting for transport, construction, use phase, and end of life handling for each material or component chosen from the calculation database. An overview of the OneClick LCA Norge NS3720 software and calculation methods are shown in Table 2. The results of the LCI, as well as a description of the case study, are given in section 5.3 and 5.1.

3.3.3 Life Cycle Impact Assessment

The greenhouse gas calculation tool OneClick LCA Norge NS 3720 was used to perform the Life Cycle Impact Assessment following the method outlined in NS 3720. The results from OneClick LCA were then extracted to excel files to be further analyzed. The results from the main analysis are presented in section 6.1 and 6.3, and the second (EPD) analysis are presented in section 6.4

In order to evaluate the relative importance of embodied emissions from the technical installations compared to the rest of the building, the results for the primary Life Cycle Assessments conducted in this thesis are also compared to LCA results from the entire building, not including technical installations, provided by Statsbygg. Only the life cycle stages included in the scope of this study are included from the LCA on the whole building. The results from this comparison are presented in section 6.2.

Table 2: Overview of OneClick LCA Norge NS 3720

Parameter	One Click LCA Norge NS 3720
Calculation method	Based on NS 3720 standard (itself based on EN 15978)
Calculation scope	Based on NS 3720 standard; always holistic building view
Emission factors	Always life-cycle based, CML IA 4.1. compliant as per EN 15804+A1, as CO_2 equivalent (as required by NS 3720)
Calculation database	Generic materials and process database and nearly all Norwegian and European EPDs
Supported energy norms	TEK10, TEK17 and updated passive house standards
Accounted impacts	Non-biogenic carbon, biogenic carbon and land use changes (LULUC) impacts separately
Materials calculation	Life-cycle based, accounting transport, construction, use phase and end of life handling(‘cradle to grave’)
Reference building method	Structural materials use is based on geometry of building and on structural engineering
Transport calculation method	Based on NS 3720, allows adjusting different user groups transport parameters separately

3.3.4 Sensitivity Analysis

Uncertainty is always present in any analysis, and this study is no exception. There are many sources of uncertainty, some of which are the amount of material used in the technical installations and the choices of material and components from the OneClick LCA database. Several assessments are made to test the sensitivity of the model results to variability between objects (differences in technology between factories that produce the same components or materials) and parameter uncertainty (inaccurate or non-representative inventory data). The following investigations are made:

- sensitivity to assumptions of component weight and thus different material amounts in components
- sensitivity to choices of equivalent components from the OneClick LCA database

- sensitivity to choices of materials used to model components lacking from the OneClick LCA database
- sensitivity to different modeling procedures of components

All sensitivity analysis is done by modeling materials and components in OneClick LCA and is made for those components with the most significant parameter uncertainty and those that show the most considerable variation between the results in the two methodical inventory structures.

4 Literature Review

In this section the result of the litterature study is presented. First, summaries of the reviewed studies are presented, followed by a discussion of the findings.

4.0.1 Reviewed Studies

Nyman and Simonson (2005) carried out an LCA of ventilation units with heat exchangers for residential houses in cold climates. The assessment includes materials and emissions from the ventilation units as well as operational energy use. However, ventilation ducts are not included. The study concluded that compared to emissions from operational energy use, embodied emissions in materials are found to be negligible.

Blom et al. (2010) performed an LCA study of the use and maintenance of heating and ventilation systems in Dutch dwellings. The study includes scenarios with gas-fired boiler or heat pumps for heating and tap-water combined with either individual balanced ventilation with heat recovery or mechanical exhaust ventilation. Material inputs from installation and maintenance of the heating and ventilation systems and operational energy use are included, though material inputs are only provided as aggregated amounts. The results show that the heat pump performs worst on all impact categories when compared to the boiler. According to the authors this is because it requires electricity to run, and in addition material recources needed to produce the heat pump is up to ten times higher than for the boiler. The study also finds that individual balanced ventilation decreases impacts for four out of nine impact categories including GWP by 3-13% compared to mechanical exhaust ventilation, and increase impacts by 7-41% for the remaining five. The increased impacts are acording to the authers caused by material content and increased operational energy of the ventilation system. However, the contribution from the material inputs compared to the total ventilation and heating system is found to be small.

Tan and Nutter (2011) assessed greenhouse gas emissions form liftime operation of HVAC systems in common commercial building types, and the influence of operating the buildings in different climate regions. The authors found that operational energy use dominant compared to the emissions from manufacture and production, which ranged from 1.9-4.2%.

In an MSc. thesis from NTNU, Sørnes (2011) performed an environmental assessment of technology alternatives for heating and ventilation of highly energy-efficient residential buildings. The author experienced difficulties obtaining inventory on a full balanced ventilation system, and as a consequence based the life cycle inventory on a product decleration of a specific system with quantities indicated as percentage of total mass. The results show that 6-7% of total climate emissions from ventilation are associated with materials, and that heat recovery completely compensates for emissions from the manufacture, maintenance, and operation of the ventilation unit. However, it was also dound that material in the ventilation system contributed to 40% of metal deplation and 30% of freshwater ecotoxicity.

Ghose (2012) carried out an LCA of a passive house with natural and mechanical ventilation in Norway. The study relied on avaliable information from other studies and adaptations from a specific system and producer for the material inventory. The share of impacts contributed to material inputs in the ventilation systems are not specified, but appear to be minor.

Kovacic et al. (2018) carried out an LCA study of three ventilation systems for a classroom; mixing ventilation, displacement ventilation, and stratum ventilation. The study includes a detailed inventory for the material inputs, which are quantified in terms of embodied energy and multiplied with a CO_2 factor of 0.7 kg CO_2-eq/kWh. The resulting contributions from embodied energy in the ventilation materials are between 1/4 and 1/3 depending on the ventilation system. It should be noted that the study is carried out for a location in Hong Kong, with Chinese technology assumptions.

Ylmén et al. (2019) assessed the emissions from an office building in Sweden through LCA based on site-specific data provided by contractors. The material inventory is only presented as distribution of material categories, and specific components or their material quantity of the included technical installations are not listed. The study reveals environmental impacts from material inputs in the HVAC system to be considerable, contributing to 14-32% of total impact in four out of five impact categories. Also, it was found that copper and aluminium contributet to 64-93% of total impact in the HVAC system. An MSc. thesis, by Borg (2016), investigates the environmental impact from the ventilation systems in a modern energy-efficient office building in Norway. BIM models are used to extract detailed data about components and dimensions of the ventilation system in a planned Norwegian office building, and both a conventional LCA analysis and a dynamic LCA approach. The embodied emissions associated with material inputs are found to be in 5% and 23%, assuming European electricity mix and Norwegian Electricity mix, respectively. The dynamic LCA approach results in the share of climate emissions ranging from 7% with a European electricity mix and 30% with a Norwegian electricity mix.

Rodriguez et al. (2020) investigated material quantities and embodied carbon in mechanical, electrical and plumbing equipment in hypothetical buildings of different sizes. The scope of the study was cradle-to-gate, and the total embodied carbon estimates for the technical installations ranged from 40-75 $kgCO_2eq/m^2$. The HVAC systems had the largest contribution, ranging from approximately 28-60 $kgCO_2eq/m^2$, while the electrical installations ranged from approximately 2-13 $kgCO_2eq/m^2$.

Kiamili et al. (2020) assessed the embodied carbon of HVAC systems for a new office building in Switzerland is performed collecting high-resolution life cycle inventory data in terms of components, dimensions, and specific material composition from BIM. The study finds the most impact intensive components to be hybrid ceiling panels and air handling units (AHU). Due to the yearly replacements of filters, they are found to contribute to 65% of the total replacement impact of the AHUs. The embodied impact of HVAC systems lies in the range of 15-36% of the total embodied impact of office buildings.

4.1 Discussion

4.1.1 Importance of Embodied Emissions in Materials and Components

The reported impact of embodied emissions in materials and components in ventilation and other technical installations varies greatly between studies. Several studies found contribution from embodied emissions in materials and components to be minor (Tan and Nutter, 2011; Sørnes, 2011; Nyman and Simonson, 2005; Blom et al., 2010; Ghose, 2012) However, more recent studies report the contribution from embodied emissions in material and components be to higher, especially studies where more comprehensive efforts have been performed to develop detailed life cycle inventories (Ylmén et al., 2019; Kovacic et al., 2018; Borg, 2016; Rodriguez et al., 2020; Kiamili et al., 2020)

These newer studies indicate that embodied emissions are more important in regards to the total environmental impact of buildings than initially recognized. The discrepancies between older and newer studies can partly be explained by improvements in the energy efficiency of buildings, thus decreasing operational energy use and increasing the relative importance of embodied emissions. Another influence is the choice of electricity mix and associated emissions, as well as an increase of renewable shares in the electricity mix in recent years. However, the studies that found relative contribution of embodied emissions in materials to be more substantial, have also included a much more detailed inventory on HVAC and other technical components compared to those that found the contribution to be minor. This indicates that as more research is carried out and inventories become more complete, the “true value” of emissions share embodied in materials could in many cases turn out to be even higher.

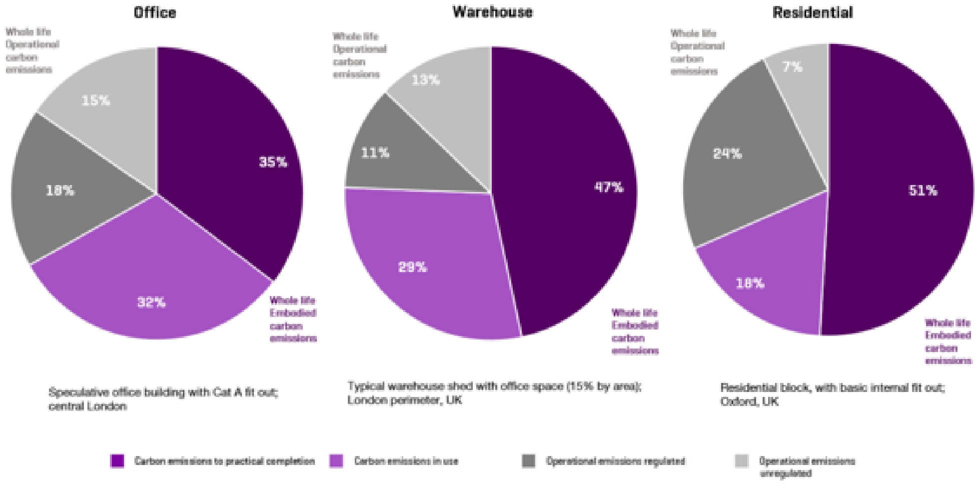


Figure 4: Total whole life carbon emissions breakdown for different building types

A 2017 report from RICS on whole life-cycle carbon assessment for the built environment further corroborates the increasing importance of embodied emissions in buildings as the renewable share in electricity mixes and energy efficiency increases (RICS, 2017). As can be seen from Figure 4, illustrating the typical breakdown of whole life carbon emissions for different building types, highlighting the relative weight of operational and embodied carbon, the relative share of total embodied emissions range from 67-76% of total carbon emissions. The whole life figures were calculated covering a cradle-to-grave scope over a 60-year life cycle, with the assumption of grid decarbonization in accordance with the slow progression scenario from the National Grid Future Energy Scenarios 2015.

4.1.2 Life Cycle Inventory Availability

There has been a shift in focus over the past decade from energy emissions in the use phase to embodied emissions in the construction of buildings. However, the focus has largely been on embodied emissions in the material content of the building facade, and technical installations are largely overlooked. Generally, the material content of technical installations and components is poorly described and documented. There is insufficient understanding of the emissions embodied in technical installations, and consequently these emissions may not be adequately addressed. This impression is reinforced in most of the studies referred to here, as well as in studies not included (Nyman and Simonson, 2005; Dokka et al., 2013; Blom et al., 2010; Sørnes, 2011). The inadequate inclusion of embodied emissions from technical installations increases the risk of problem shifting, both between impact categories, as discussed in some studies (Sørnes, 2011; Ylmén et al., 2019; Borg, 2016), and life cycle phases.

Different methods and sources have been used to obtain information about material inputs for ventilation and other HVAC systems, and most of the studies cited specifically mention that life cycle inventories for ventilation systems or technical components are a challenge when performing LCAs of buildings. Yet, very few studies actually take this into account (Sørnes, 2011; Ghose, 2012; Kovacic et al., 2018; Borg, 2016). Instead, as also found in other literature (Bergsdal, 2020), ventilation systems are often omitted, included as an estimated increase in total embodied emissions, or included in a primitive manner based on simplified inventories (Tan and Nutter, 2011; Sørnes, 2011; Nyman and Simonson, 2005; Blom et al., 2010; Ghose, 2012). The most detailed inventories are obtained from BIM models (Borg, 2016; Kiamili et al., 2020) or from project-specific tendering documents(Ylmén et al., 2019). These are favorable approaches as they offer high resolution in terms of dimension, number, and material composition of components, however, these approaches are time-consuming.

4.1.3 Operational Emissions and Electricity Mix

The assumption of electricity mix for operational energy use may be the most influential factor on both the relative importance of embodied emissions and total emissions related to HVAC systems. Naturally, less emission intensity in the electricity mix will reduce the operational energy emissions, decreasing the total emissions from HVAC installations while simultaneously increasing the relative share from embodied emissions. This is especially true for assumptions of Norwegian electricity mix because of the extremely high renewable shares.

Because of the long lifetime of buildings, electricity mix assumptions also imply an assumption about emission intensities of future electricity mixes, meaning this is also a factor with substantial uncertainty. In some studies, long-term scenarios for electricity mix emissions and grid decarbonization are used and included in the studies as an average emission factor per kWh (RICS, 2017; Wiik et al., 2018). Other studies address this uncertainty and discuss or test sensitivity to the electricity mix (Tan and Nutter, 2011; Sørnes, 2011; Ghose, 2012; Borg, 2016). . Since Norway is increasingly connected to the Nordic and European market and increased renewable shares are expected to bring emission intensities down in Europe generally, this assumption seem a reasonable compromise for a long-term emission profile (Litiu, 2012).

4.1.4 Technical Installations

As discussed in section 4.1.2, embodied emissions from technical installations are generally omitted or inadequately covered due to lack of data availability. Even in the studies employing the most detailed life cycle inventories, there are component groups that are left out altogether or if included based on highly simplified inventories. This is especially true for electrical equipment and systems. Electronic components and wiring, if at all included, are generally based on crude assumptions. Only a few of the cited articles included emissions from electrical installations in general(Ylmén et al., 2019; Rodriguez et al., 2020), and only one of the studies included electrical components connected to ventilation, heating or cooling systems (Kiamili et al., 2020).

The increasing complexity of technical installations in buildings is often associated with better control and monitoring, meaning more equipment to do exactly that. However, none of the studies referred to, or studies not included, discuss the potential increase in energy use control and monitor equipment. In addition, as Bergsdal (2020) discusses, concern has been raised about failure rates, lifetime and replacement intervals of control equipment, sensors and other small electronic equipment in buildings. Very often, as a way of troubleshooting for an unknown problem and assure the reliability of the component, sensors and control equipment are replaced rather than repaired. He argues that LCA studies don't account for the unexpected failure of such components, but if included are only based on expected component lifetimes. Kiamili et al. (2020), the study investigated with perhaps the most detailed life cycle inventory and accountancy for replacement of equipment have estimated replacement frequency based on a most-likely scenario using combined information from manufacturers and the ASHARE standard. However, whether or not this actually includes unexpected failure of components is not clear. Furthermore, the replacement of control equipment and sensors are not specifically addressed, so if at all accounted for are baked into the embodied emissions from the replacement of larger mechanical equipment.

Another aspect rarely discussed in literature in regards to maintenance and replacement of equipment is the fact that this not only increases emissions related to additional component manufacture but also entails additional labor use and transportation. Borg Borg (2016) does include environmental impacts related to labor activities for maintenance based on economic cost, but it is not detailed for individual components. While Kiamili et al. (2020) does detail the environmental impact related to the replacement of individual components and equipment categories, whether this is just based on manufacture or also includes environmental impact due to labor and transportation is not clear.

4.1.5 Environmental Impact Categories

Generally, the focus on climate change and global warming mean LCA studies in buildings also tend to focus on CO_2 related emissions, and other impact categories are given less attention or not included. All the studies investigated assessing the environmental impact of ventilation systems or other technical installations, included and not, include climate emissions and global warming potential as the main impact category. In order to avoid problem shifting, and creating new problems while trying to alleviate another, it is important for LCA studies to have a wider perspective on potential environmental impacts. All the studies included that looked at more than one impact category, found embodied emissions in technical installations to be significant for impact categories other than global warming potential. As shown in figure 5, Ylmén et al. (2019) found that HVAC installations contribute in the range of 14-32% in four out of five of the assessed impact categories.

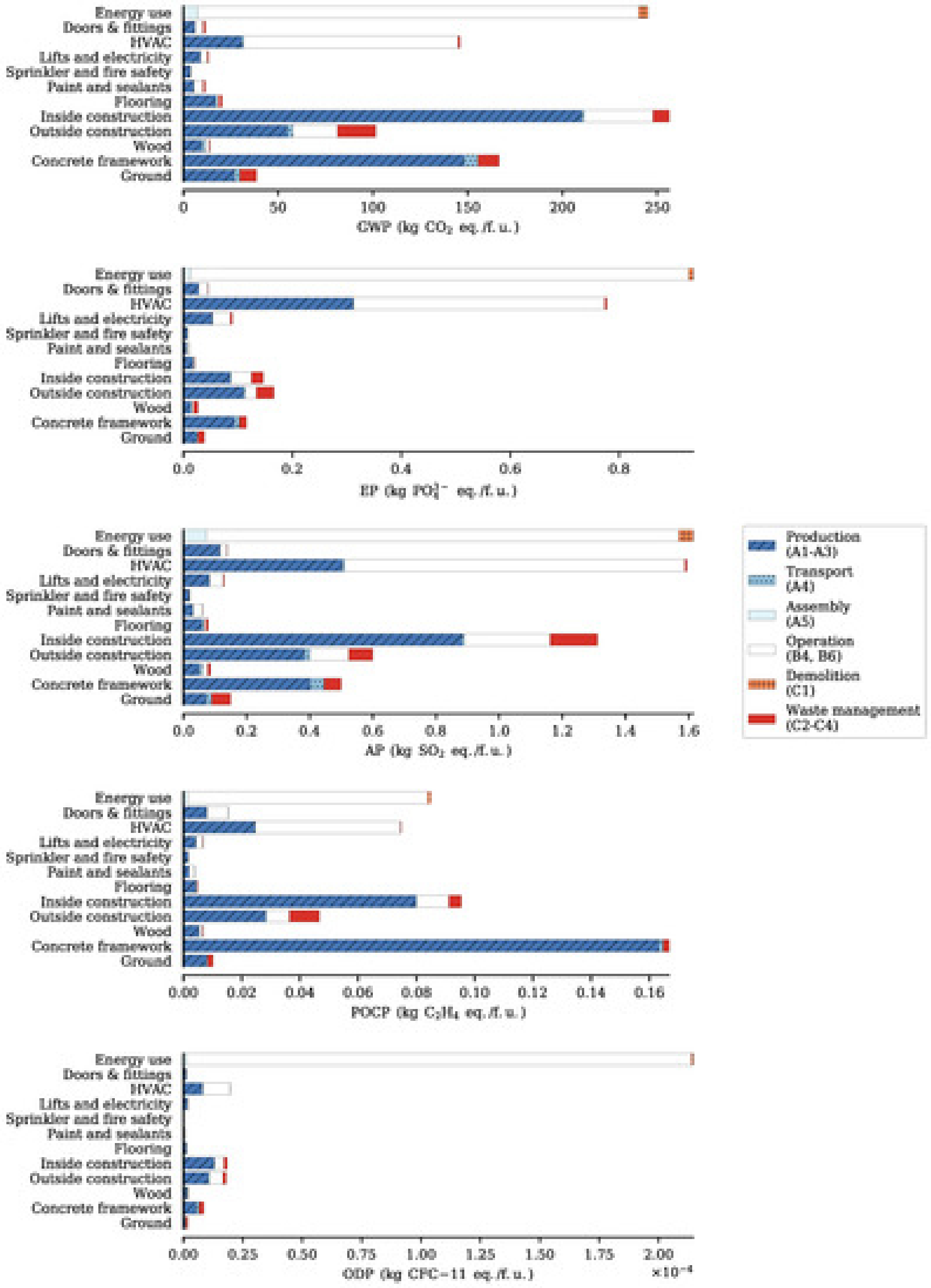


Figure 5: Impact of the different parts in the building for the environmental impact categories investigated by Ylmén et al. (2019)

Even studies where technical installations are only partly covered or included with generic estimations and the contribution of embodied GHG emissions was deemed to be minor, found the environmental impacts embodied in ventilation systems to be of importance to categories such as metal depletion and freshwater ecotoxicity(Sørnes, 2011). This indicates that more complete life cycle inventories are expected to further increase the importance of embodied emissions in technical installations. Furthermore, Ylmén et al. (2019) found that materials such as copper and aluminum accounted for 64-93% of the environmental impact in the HVAC system. These materials are also commonly used for electrical wiring, thus indicating similar relationships can be expected for other technical equipment such as electrical power systems.

4.1.6 BIM as a Tool for LCA Analysis

Life cycle assessment is a powerful tool for calculating environmental impacts during the entire lifecycle of a building. However, there are many factors that need to be taken into account in order to get an accurate picture of the importance and range of those impacts. As discussed in sections 4.1.2 and 4.1.4, a major limitation for achieving sufficient precision with regards to the environmental impact is the access to and collection of data. As pointed out 2.4, Building Information Model or BIM is a powerful tool for providing detailed information about building components, and can therefore be an important tool in developing high-resolution life cycle inventories, which is also demonstrated in several of the studies included here (Borg, 2016; Kiamili et al., 2020).

Potrč Obrecht et al. (2020), found in a systematic literature review of 60 papers on BIM and LCA integration that information from BIM models is predominantly manually or semi-automatically imported into the LCA tool. The process of integrating BIM and LCA is still at an early stage, and the authors identified three major issues of the integration process:

- creating a synchronized LCA methodology that enables a clear identification of the inputs needed
- developing information databases that ontologically and semantically conform to the BIM environment, and that also correspond to the desired design phase of the project
- creating a flawless and automated exchange of information between BIM and LCA tools, regardless of whether they are embedded in the BIM environment or used as separate files

The study concludes that while an optimized integration of BIM and LCA, where users have an overview of the entire range of processes and material flows during the entire life cycle of the building, will generate replicable and trustworthy LCA results and lead to an improved building design process, there is still a long way to go. Therefore, manual or semi-automatic importation of data is still deemed more accurate as it allows the user more control over the stages and processes that are included in the assessment.

Stadel et al. (2011), conclude from their work with LCA plug-ins in BIM programs that these tools are not precise enough when compared to results from dedicated LCA tools such as OneClick LCA or SimaPro. The authors find one of the main challenges in using BIM for LCA is the varying detail level of the BIM models in regards to individual material estimates. As an example, a concrete wall with wooden studs may be presented as a compact wall instead of showing its separate concrete and wooden components.

5 Case Study

5.1 Description of the Ocean Space Center and Wing A

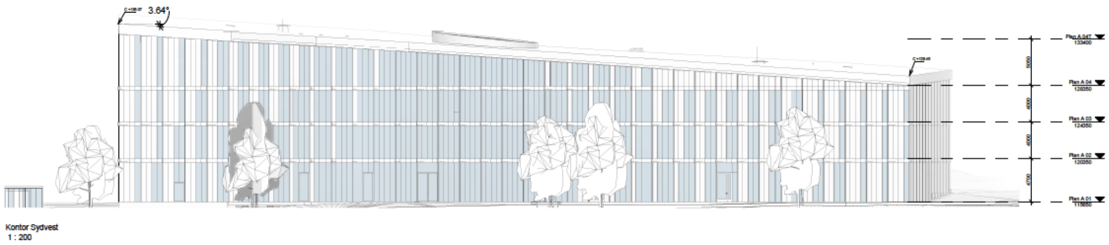


Figure 6: Southwest facade of the new building in wing A of the Ocean Space Center, Image: Snøhetta

The Ocean Space Center (OSC) will be one of the world's most advanced facilities for research and teaching of the sea and the opportunities that lie in the ocean space. The center will be the national knowledge center for ocean space technology and located at Tyholt in Trondheim. The Ocean Space Center shall include wet and dry laboratories with ocean basins, construction and machine laboratories, teaching rooms and teaching laboratories, office, and meeting rooms. The laboratories will contain very advanced equipment. The building will consist of three different buildings, referred to as wings A, B, and C, and a total of approximately 49,000 sqm. Wing A will consist of one already existing and partially listed building (Tankhodet) and a new construction of approximately $9000m^2$. It is this new construction of wing A which has been analyzed in this thesis.

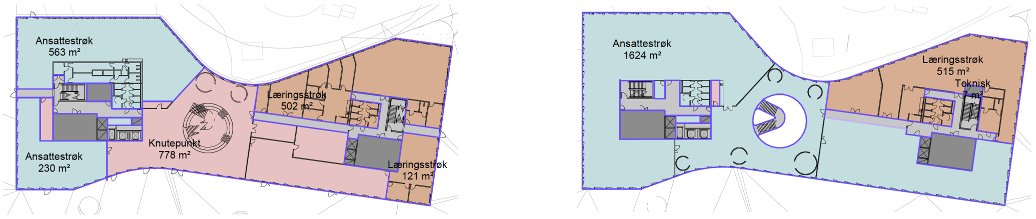
Given investment approval from the Norwegian Parlement in December 2021, the project start is set in January, with construction starting in August of 2022. If approved, Statsbygg will be the contractor, The Norwegian University of Science and Technology (NTNU) will own the buildings and premises, and SINTEF will rent premises and laboratories from NTNU. Wing A will be dedicated workplaces for employees at NTNU and SINTEF, as well as learning areas, student workplaces, common areas, and communication. The new building will consist of two parts with five floors to the west and four floors to the east. The west wing on floor three and floors four and five in their entirety is dedicated workplaces for SINTEF and NTNU. The entire floor plan can be seen in Figure 7. This part of the Ocean Space Center has been chosen as the subject of this study since it does not contain any wet or dry laboratories. Thus the technical installations in this wing will be more comparable to other office or university buildings. An overview of the type of zones and their area is given in Table 3. Henceforth, the new building of wing A will be referred to as wing A.

The project will comply with the passive house standard for office and teaching buildings and is set to have a BREEAM certification at level "Excellent." The center will be an almost zero energy building due to solar cells and heat recovery. The construction site will be fossil-free, with as large a proportion of emission-free machines as possible. For the outdoor area, Statsbygg's ambition is to increase the blue-green factor and for the project to preserve and increase biological diversity.

Table 3: Gross floor area (GFA) and heated floor area (HFA) as given in the planning documents for Ocean Space Center

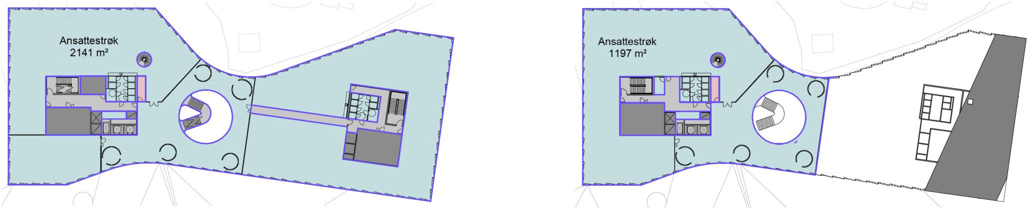
Area per zone wing A OSC

Type of sone	Area $[m^2]$
Employee Workplaces	5787
Teaching and student zone	1138
Common area	830
Hallways	836
Technical room	545
Total GFA	9136
Total HFA	8747,5



(a) 1st Floor

(b) 2nd Floor



(c) 3rd Floor

(d) 4th Floor

Figure 7: Floor Plan of the new construction of wing A - Image: Snøhetta

The plumbing, heating, and sanitation installations are dimensioned according to BREEAM specifications and governmental regulations. The building will be equipped with a waterborne heating system with geothermal heat pumps and district heating to cover tap water, space heating, snow melting systems, and ventilation heating needs. Space heating will be done by waterborne underfloor heating or radiators. The cooling demand is assumed to be covered via free cooling via geothermal wells, and the building will be cooled with ventilation air via a waterborne system. All areas will be ventilated with balanced ventilation. The principle of displacement ventilation is planned in areas with large volumes and agitation in closed and delimited rooms with ceilings. Variable Air Ventilation will be used to the extent it is possible and will be demand-controlled according to combined CO_2 and temperature sensors.

The building will be supplied with electricity from the grid and a $500m^2$ photovoltaic system. Guideways for cables are established, partly in pipes in decks and partly as cable ladders from the main switchboard to central places in the building. General lighting in the ceiling combined with additional lighting at workplaces will be used to satisfy lighting requirements in accordance with ”Lyskulturs tabeller for luxverdier.”

5.2 Gathering of Component Data

What was possible to gather of component quantities and material data for the ventilation and electrical systems was collected from BIM-models for the respective disciplines in IFC file format provided by Statsbygg. The BIM-models provided are from an early stage in the design phase and limited to the ductwork and air handling units (AHUs) for the ventilation system and cable carrying systems and transformers for the electric power installations. Component lists were extracted using Information Takeoff in Solibri and Quantity Schedules in Revit and exported to Excel spreadsheets for further analysis and data structuring. Statsbygg provided data on PV panels and geothermal heat pumps.

To improve the inventory resolution, additional BIM-models from HVL Bergen were used to map the scope of technical equipment. The quantity extraction was provided by Alexander Borg and Elena Dalen, both a part of the ZEN Case working group for OSC. The data was taken from the "as-built" ventilation model and pipe model. Both IFC files are included in Digital Appendix A. Information extraction from the ventilation system was limited to an area of $2231m^2$ GFA which is supplied by one ventilation system (360.001) and serves offices, multi-rooms, work zones, social zones, and various support functions located in U.-5 floors. Information extraction from the heating system and comfort cooling system was taken from an area of $14411m^2$ GFA, (320.001 and 370.001) which also serves offices, multi-rooms, work zones, social zones, and various support functions located in U.-5 floors.

The results of the quantity extraction for ventilation components and heating-cooling components is listed Appendix 10, in Tables 13 and 14, respectively, where components are summed up in kg and pieces, as well as average quantities per square meter GFA.

5.2.1 Data Quality

In NS 3720:2018 there is a distinction between two levels of data quality:

level 1 refers to data that has been calculated or measured for a tangible product or specific service. Data must reflect the actual product or service.

level 2 refers to all data not satisfying the quality requirement at level 1. All generic, representative, and average data are calculated based on specific data for a production process.

All data used in this analysis should be considered to be of data quality 2. This is because all components are, to some degree, based on assumptions, either in the form of amounts, material, or manufacturer. Even the most accurate data on components, amounts, and manufacturers collected in the LCI are not necessarily modelled as the exact component in OneClick LCA due to availability in their databases.

5.3 Description of Components

Where applicable, inventory data was used directly in OneClick LCA on a component basis. The weights were taken from datasheets from manufacturers or EPDs for specific components. In cases where the component sizes did not precisely match, the given data was interpolated to give the correct weights and sizes. It should be noted that, with a few exceptions, it was not stated in the IFC files which specific component will be used, so the specific component data used in this analysis may vary from the actual building. All data sheets and EPDs used to extrapolate weights and material amounts are supplied in Digital Appendix B.

In some cases, given components are not available in the OneClick LCA database. Therefore different methods were used to model components in OneClick LCA. One of the following three procedures, listed in prioritized order, was used:

1. Modelled as equivalent component (same component with similar or same characteristics).
2. Modelled as a similar component (for example, duct and pipe fittings as circular duct/pipe or a specific type of valve as a different similar valve).
3. Modelled as different materials, based on the given material amounts for the specific component. Material amounts less than 2% are omitted.

322 and 372 - Pipe Network for Heating and Comfort Cooling

All pipes and pipe fittings are assumed to be in steel. All amounts are based on amounts from HVL Bergen and estimated by multiplying the amount/GFA from HVL with the GFA from the OSC. The specific amounts for heating and comfort cooling, respectively, are given in Table 4.

Pipes: The material amount of pipes in kg from HVL was estimated and provided by Elena Dalen. The amount was converted to OSC and modelled in OneClick LCA according to procedure 1 in the generic model and procedure 2 in the product specific model.

Pipe Fittings: The pipe fittings include all bends, plugs, and connection pieces and are estimated as 15% of the pipe weight. They are modelled with the assumed weight as the same component used for the pipes in the respective LCA models, meaning procedure 2.

322 and 374 - Fittings for Heating/Comfort-Cooling Installations

All element amounts are based on amounts from HVL Bergen and estimated by multiplying the amount/GFA from HVL with the GFA from OSC. The specific amounts for heating and comfort cooling, respectively, as well as types of valves, are given in Table 4.

Valves: Valves are a type of throttling device used to regulate the flow through the pipes, radiators and cooling coils. There are many different types of valves, and the specific types and amounts used in this study are based on information from the HVL rør IFC file and datasheets are used to extrapolate weights. All valves are modelled in OneClick LCA using procedure 1 or 2, when procedure 2 is used the valves are modelled using weight instead of units.

325 and 375- Equipment for Heating Installations

All element amounts except for heat pumps are based on amounts from HVL Bergen and estimated by multiplying the amount/GFA from HVL with the GFA from OSC.

Geothermal Heat pumps: A type of heating/cooling system taking advantage of the relatively constant temperatures in the earth, using a heat pump to transfer heat to or from the ground. Data on the geothermal heat pumps were provided by Statsbygg and modelled in OneClick LCA as heat pumps with fitting characteristics.

Circulation Pumps: These are centrifugal pumps designed to generate forced circulation in the pipe system. No data was provided on the type of pumps and were modelled as circulation pumps available in the OneClick LCA database.

Radiators: Hot water radiators to supply heat to rooms or areas in the building. No data on the specific type of radiators were found. They are modelled in OneClick LCA based on the installment of kW they projected to deliver.

Cooling coils: cooling coils are units in waterborne cooling systems used to transfer heat from the air, thus cooling it. No data on the type of cooling coils were found. Weight and material composition were extracted from datasheets from Trox Auronor and modelled in OneClick LCA according to procedure 3.

Air Separators: Air separators are used to separate entrained air in the circulating medium through forced flow patterns.

362 - Duct Network for Air Treatment

All ducts and duct fittings are assumed to be galvanized steel.

Circular Ducts: Weights of circular ventilation ducts were taken from datasheets and modelled with their specific diameter and length, or by weight, using environmental data from the OneClick LCA database, i.e., procedure 1.

Rectangular Ducts: Weights were were taken from datasheets and modelled by procedure 2 in the generic case and procedure 2 in the EPD case.

Circular Bend: Weights were taken from datasheets for circular bends and modelled as ventilation ducts in OneClick LCA.

Rectangular Bend: Dimensions were taken from datasheets for rectangular bends, and weights were then interpolated from data on rectangular ducts. They are modelled as ventilation ducts in OneClick LCA.

Plugs: Plugs are end pieces for circular and square ducts, the weights of circular ducts were given from datasheets, and the rectangular ducts were interpolated from rectangular ducts based on material amounts. They are modelled as ventilation ducts in OneClick LCA.

Connection Pieces: Connection pieces are 90$\circ$ branch connections or reduction pieces connecting two ducts of different sizes. Material amounts are taken from data sheets and interpolated from rectangular or circular ducts to find weights. They are modelled as ventilation ducts in OneClick LCA.

364 - Equipment for Air Distribution

All components within this group are based on amounts from HVL Bergen. The amount for each component is estimated by multiplying the amount/GFA from HVL with the GFA from OSC and the ratio of ducts between HVL and OSC. All galvanized steel in any of the components is modelled as ventilation ducting, as it is assumed this better captures the resulting emissions from the production of the component.

VAV Dampers: The VAV dampers are flow volume regulators that work independently of the duct pressure. The VAV unit is based on the dynamic measurement of air volume and regulates the damper position to maintain the desired air volume. The number of different types of dampers, their weight, and material amounts are based on component information from the HVL ventilation IFC files. All dampers are modelled according to procedure 3.

Supply and Extract Air Units: These devices are used to supply and extract air in or out of a room or area inside the building and are often interchangeable. They come in many different sizes and models, with and without plenums, and measure and regulate units for variable air volumes. The type of unit and their weights and material amounts are taken from datasheets based on component information from the HVL ventilation IFC file. They are modelled according to procedure 2 in the generic case and procedure 3 in the EPD data case.

Fire Dampers: Fire dampers are used to prevent the spread of fire, smoke, and toxic gases through ventilation ducts with a mechanical spring release mechanism preventing air circulation in the event of a fire. The fire dampers are modelled according to procedure 2.

365 - Air Treatment Equipment

Air Handling Unit: The air handling units (AHUs) for the system is Geniox 29 supplied by System Air. It is an aggregate with a rotary heat exchanger and frequency-regulated EC motors. The AHUs are modelled as similar air handling units in OneClick LCA.

Intake and Exhaust fan: The intake and exhaust fans are rooftop exhaust hoods, supplying the ventilation system with fresh air and disposing of the exhaust air. The component information is taken from the OSC BIM files and modelled in OneClick LCA according to procedure 2.

Silencer: The silencers are circular and square sound attenuators with circular end spigots. The component amounts are based on HVL Bergen and are estimated using the same procedure described for building elements 364. Weight and material are taken from datasheets based on component information from the HVL ventilation IFC file and modelled according to procedure 3 in OneClick LCA.

411 - Cable Carrying Systems

Cable Ladder: The lengths of cable ladders were taken from the OSC IFC files, and weights were taken from datasheets. They were modelled in OneClick LCA using procedure 2.

Cable Ladder Bends: The weights of bends were extrapolated from datasheets for cable ladders, and modelled according to procedure 2.

433 - Electrical power distribution for common use

Cables: No data was provided on the amounts or type of cables used for electricity distribution cables. However, an estimation on the amount of cables was done based on the norwegian average per m^2 for similar building types provided in the OneClick LCA database.

442 and 443 - Lighting Equipment and Emergency Lighting

Light fixtures: Amount and types of light fixtures are based on data from HVL Bergen and estimated using the same method as for heating and comfort cooling. All light fixtures are modelled according to procedure 2.

Emergency lights: Amount and types of emergency lights are based on data from HVL Bergen and estimated using the same method as for heating and comfort cooling. All light fixtures are modelled according to procedure 2.

449 - PV panel

Solar Panels: The data on the PV panels on the building was provided by Statsbygg, and are modelled in OneClick as panels with similar characteristics.

Table 4 shows a breakdown of all the component groups and amounts categorized according to the table of building elements. The complete inventory can be found in Digital Appendix C.

Table 4: Amount of each component group categorized according to the table of building elements

2-digit Building Element	3-digit Building Element		Component Group	Amount	Unit
32 Heating	322	Pipe network for heating	Galvanized Steel Pipes	8925	kg
			Pipe Fittings	1339	kg
	324	Fittings for heating installations	Ball Valves	417	p
			Balancing Valves	6	p
			Thermostat-controlled Radiator Valves	55	p
			Radiator Control Valves	154	p
	325	Equipment for heating installations	Geothermal Heat pumps	3	p
			Pumps	9	p
			Radiators	173	p
			Flters	1	p
			Air Separator	1	p
			Expansion System	1	p
	326	Insulation for heating installations	Insulation	519	m^2
36 Air Treatment	362	Duct network for air treatment	Rectangular ducts	142	m
			Circular ducts	726	m
			Plugs	46	p
			Rekt. Bends	10	p
			circular bends	81	p
			Connection pieces	35	p
	364	Equipment for air distribution	VAV dampers	146	p
			VAV Supply air units	162	p
			Supply air vents	216	p
			Extraxt vents	162	p
			Fire Dampers	7	p
	365	Air treatment equipment	Air Handling Units	7	p
			Silencers	368	p
			Inntake and Exhaust fan	4	p
	366	Insulation for air distribution	Insulation	2645	m^2
37 Comfort cooling	372	Pipe network for comfort cooling	Galvanized Steel Pipes	11609	kg
			Pipe Fittings	1741	kg
	374	Fittings for comfort cooling	Ball valves	206	p
			Butterfly Valves	6	p
			Balancing valves	109	p
			Thermostat-controlled radiator valve	93	p
			Two-way valves cooling coil	4	p
	375	Equipment for comfort cooling	Pumps	7	p
			cooling coils	86	p
			Flters	1	p
			Air Separator	1	p
			Expansion System	1	p
	376	Insulation of comfort cooling installations	Insulation	546	m^2
41 Basic installations for electric power	411	Cable carrying systems	Cable Ladder	800	m
			Cable Ladder Bends	36	m
43 Low voltage power supply	433	Electrical power distribution for common use	Cables	20692	kg
44 Light	442	Lighting equipment	Light Fixtures	2066	p
	443	Emergency lighting	Emergency Lights	287	p
49 other electrical installations	491	PV panel	PV Panels	500	m^2

5.3.1 Estimating Insulation Amounts

No data on insulation amounts are included in the BIM files from OSC or HVL Bergen. However, based on planning documents for the HVAC systems, insulation amounts have been estimated.

Ventilation system According to planning documents, fresh air intake and exhaust ducts for the AHUs and all channels for cooled air should be externally insulated with diffusion-tight lamella mats. Insulation amounts were estimated using Ventistål's online insulation calculation tool. Thickness is assumed to be 100 mm, and insulation type is assumed to be Glava lamella mats.

Heating system Planning documents state that all pipelines, connections, valves, etc., to the heating system, except connection lines to radiators. Insulation thickness is assumed to be 35 mm and of the type Glava Climpipe Section ALU2. Insulation amounts for pipelines were estimated by the following method:

1. Finding the average diameter of heating pipes from the HVL component extraction
2. Calculating the weight and external area of 1m of pipe with this diameter
3. Dividing the total weight of pipe and pipe fittings with the weight of 1 m pipe and multiplying with the external pipe area to find the total area that should be insulated

Insulation amounts for valves, pumps, etc. was estimated for a simplified geometrical shape.

Comfort cooling system As stated in the planning documents, insulation of cooling pipes must be performed with diffusion-tight insulation. All fittings and equipment, such as valves, pumps, etc., must be insulated. The insulation amounts were estimated using the same method as for the heating system. Insulation was assumed to be from elastomeric foam (cellular rubber), and the thickness was assumed to be 19 mm.

5.4 Lifetime of Components

Estimating the expected lifetimes of each component included in the study is important to correctly encompass the total material use throughout the time scope of the study. This is especially true for technical installations, where many components have a shorter expected lifetime than the time scope and will therefore have to be replaced one or more times. The expected lifetime of many components of technical installations from an economic perspective is given in NS-EN 15459-1:2017 'NS-EN 15459-1:2017 Energy performance of building - Economic evaluation for energy systems in buildings. Part 1: Calculation Procedures, Module M1-14' (2018). Expected lifetimes for components not available from the standard were taken from datasheets or EPDs. As the manufacturer's data might be biased and thus overestimated, the standardized values are deemed more reliable. The relevant data on component lifetime is given in Table 5.

Table 5: Expected lifetime of components as given by Standard NS-EN 15459

Component Group	Expected Lifetime (years)
AHUs	25
Air grills	20
Dampers with control motors	15
Diffusers	20
Duct systems	30
Fans	20
Fire dampers	15
Heat pumps	20
Piping system	30
Pumps - circulation	20
Radiators, water	30
Silencers	30
Valve - thermostatic	20

5.5 Construction Site Operation Emissions

Emissions from the construction site is estimated using the construction site scenario "Average construction site impacts - Nordics, with 100 % biodiesel (per GFA)" from the OneClick LCA database. The assumed average production of construction waste is 12.6 kg/m^2 (GFA) and shares for wastes are: 59 % soil and stone-based waste, 27 % wooden waste, 12 % metal waste, 2 % other construction waste. Assumed electricity use is 43 kWh/m^2 (GFA) with an emission factor of 0.034 $kgCO_2eq/kWh$ (Norway 2015). Assumed total use of biodiesel is 6.0 l/m^2 (GFA) with an emission factor of 0.95 $kgCO_2eq/l$. (OneClick LCA database)

6 Results

This section presents the results from the Life Cycle Impact Assessment. First, the life cycle impacts of the technical installations calculated using generic data from the OneClick LCA database are presented in section 6.1. Next, the contributions of the technical installations in comparison to the rest of the building are presented in section 6.2, and a breakdown of the LCA results per component is presented in section 6.3. Finally, in section 6.4, the resulting GHG emissions from the technical installations using generic and EPD data are compared.

All results are presented for the entire lifetime of 60 years and per m^2 heated floor area, which is equal to $8747,5m^2$.

6.1 Life Cycle Impact Assessment Results - Generic Data

The Global Warming Potential from the technical installations, calculated using generic data, throughout the 60 year lifetime of the building is given in Table 6. The total Global Warming Potential is 258,9 $kgCO_2eq/m^2$. The results show that the replacement of components has the largest climate change impact, approximately 50 % higher than the impact from the production stage, which is the life cycle stage with the second-largest impact.

Table 6: Embodied environmental impacts to climate change from technical installations using generic data

Climate Change Impact [kg CO_2 eq/m^2]	
Life Cycle Modules	**Generic Data**
Production (A1-A3)	99,105
Construction (A4-A5)	9,986
Replacement (B4)	149,573
End of Life (C1-C4)	0,253
Total	258,917

The total results for all 3-digit building elements are shown graphically in Figure 8. The specific components belonging to each building element group can be seen in Table 4 in section 5.3. The results for each 3-digit building element are separated into the assessed life cycle modules.

The results become more complex when the entire life cycle of the building is considered. As seen from the figure, the impact from replacement throughout the building's lifetime, B4, is increased compared to the production phase for nearly all building elements.

The building element with the highest climate change impact from the production stage (A1-A3) is 362, duct network for air treatment, with a GWP of 19,8 $kgCO_2eq/m^2$, followed by 364, equipment for air distribution, at 12,4 $kgCO_2eq/m^2$. However, the highest total impact is from building element 364, with 47,3 $kgCO_2eq/m^2$. The end of life phase is a minor contributor for all building elements, which is also true for the total climate change impacts shown in Table 6.

It is noteworthy that the 2-digit element group with the most significant contribution to total GWP, the ventilation system (2-digit building element 36), with a total contribution of 126,5 $kgCO_2eq/m^2$, is 1,7 times higher than the following group, which is the electrical installations (2-digit building elements 41-49) with a total contribution of 74,05 $kgCO_2eq/m^2$. The impact results from each building element component group are further investigated in section 6.3.

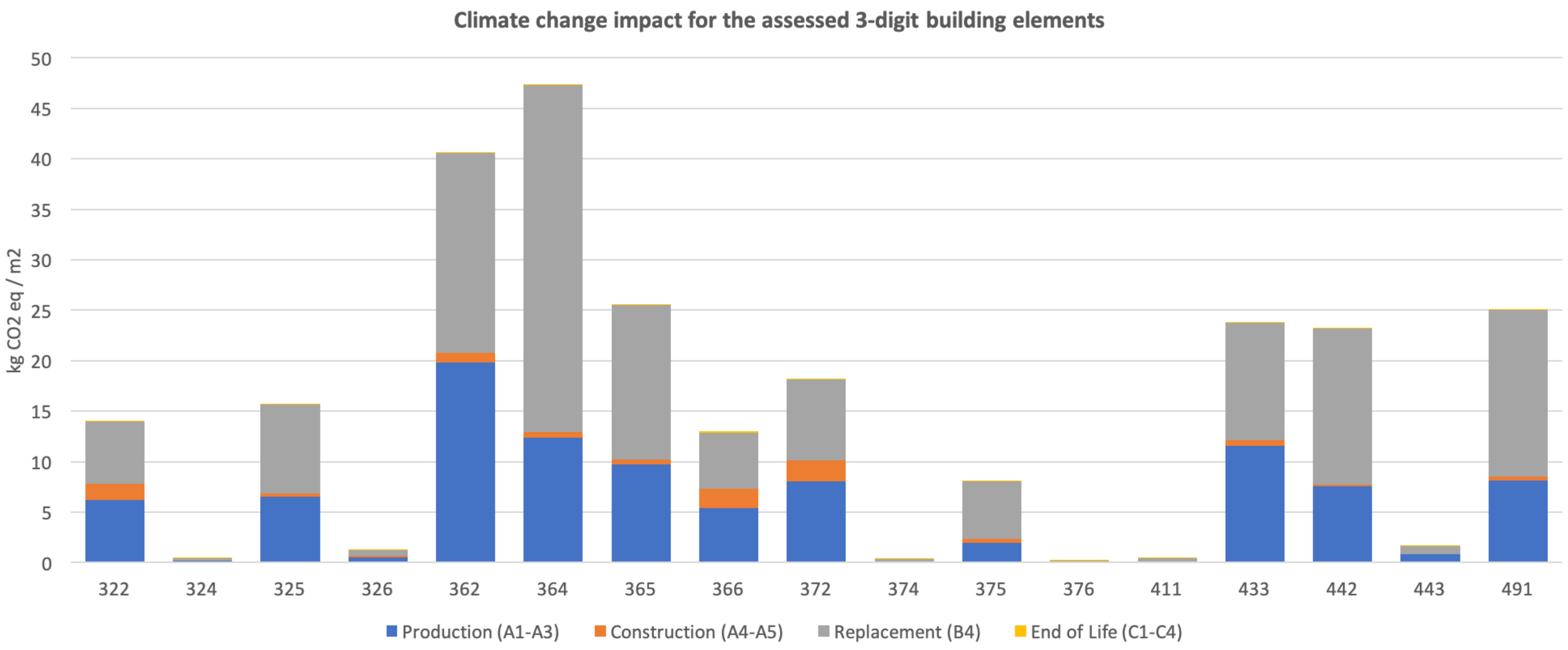


Figure 8: Climate change impact for the assessed building elements in kg CO_2eq/m^2 using generic data

6.2 Technical Installations Emission Share of the Whole Building

This section compares the life cycle impact results in each investigated module with the rest of the building to show the relative importance of embodied emissions from technical installations. Figure 15 shows the GWP percentage share of total embodied emissions from wing A, as well as the percentage share within each life cycle module. The technical installations make up 46% of the building's total embodied emissions. Due to the high frequency of equipment replacement, technical installations contribute to 85% of total GWP from B4 replacement. The only percentage share lower than 28 % for the investigated modules is C1-C4 with only a 2% contribution.

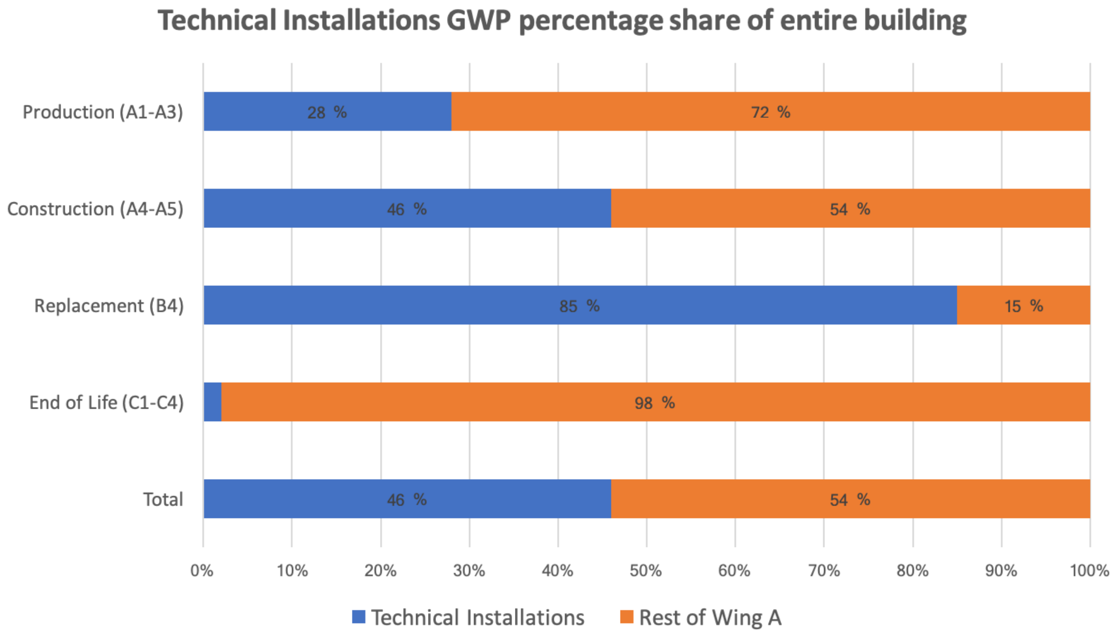


Figure 9: Technical installation GWP percentage share of the total embodied emissions for wing A - calculated with generic data

6.3 LCA Results per Component Group

In the following section, results from the investigated modules are explored in greater detail. Results for all of the 2-digit building element groups are presented graphically, showing the GWP percentage share of individual components or component groups within their group. The Global Warming Potential of each component or component group is also presented.

6.3.1 32 - Heating

The GWP percentage share of each component group is shown in Figure 26, and the various components within this building element group and their GWP are shown in Table 15.

The largest contributor to this building element group is the pipe and pipe fittings, contributing with 45% of the group's total GWP, 13,973 $kgCO_2eq/m^2$. The second-largest contributor, with 28% and a GWP of 8,630 $kgCO_2eq/m^2$, are the radiators, followed by the heat pumps contributing 21% and a GWP of 6,545 $kgCO_2eq/m^2$.

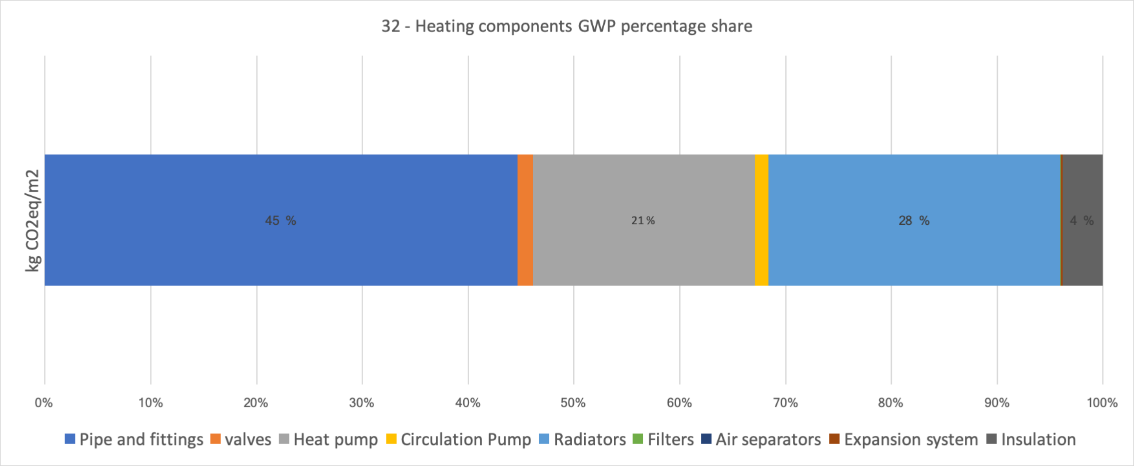


Figure 10: GWP percentage share of the included heating components for the assessed lifecycle stages (A1-A3, A5-A4, B4, C1-C4)- calculated with generic data

Table 7: Contribution of the heating components to the overall GWP for the assessed life cycle stages (A1-A3, A4-A5, B4, C1-C4)- calculated with generic data

Component	**Amount**	**Unit**	**GWP** ($kgCO_2eq/m^2$)
Pipe and fittings	10264	kg	13,973
valves	632	p	0,471
Heat pump	3	p	6,545
Circulation Pump	9	p	0,416
Radiators	173	p	8,630
Filters	1	p	0,006
Air separators	1	p	0,007
Expansion system	1	p	0,046
Insulation	519	m^2	1,203
Total			31,297

6.3.2 36 - Air Treatment

Similarly, Figure 11 and Table 16 show the GWP percentage share and total GWP contribution of the ventilation components. The total GWP of the ventilation system of 126,5 $kgCO_2eq/m^2$ is just exceeding four times that of the heating system.

As expected, the ducts and duct fittings are the most significant contributor to total GWP, with 40,596 $kgCO_2eq/m^2$. More surprisingly, they are closely followed by supply and extract air units contributing 40,172 $kgCO_2eq/m^2$, only 1% fewer emissions. The remaining elements range from 41-99% fewer emissions, though the AHUs, insulation, silencers, and dampers make a noteworthy contribution.

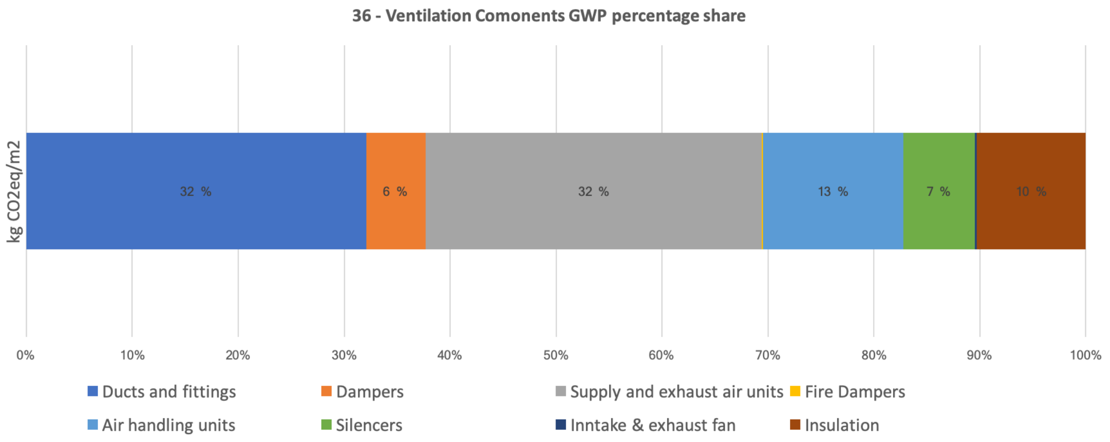


Figure 11: GWP percentage share of the included ventilation components for the assessed lifecycle stages (A1-A3, A5-A4, B4, C1-C4)- calculated with generic data

Table 8: Contribution of the ventilation components to the overall GWP for the assessed life cycle stages (A1-A3, A4-A5, B4, C1-C4)- calculated with generic data

Component	**Amount**	**Unit**	**GWP** ($kgCO_2eq/m^2$)
Ventilation ducts	24065	kg	40,596
Dampers	246	p	7,072
Supply/extract air units	540	p	40,172
Fire Dampers	7	p	0,083
Air Handling Units	7	p	16,791
Silencers	368	p	8,523
Inntake/extract fan	4	p	0,236
Insulation	2645	m^2	13,034
Total			126,508

6.3.3 37 - Comfort Cooling

The comfort cooling system emissions are 82,8% lower than the emissions from the ventilation system and 14% lower than the heating system. As shown in Figure 12, there are only two component groups that make up the main percentage share of the total GWP from comfort cooling. The pipe and pipe fittings have the highest impact with 68%, followed by cooling coils contributing to 29%. The remaining elements have between 97,7-99,9% fewer emissions (Table 17).

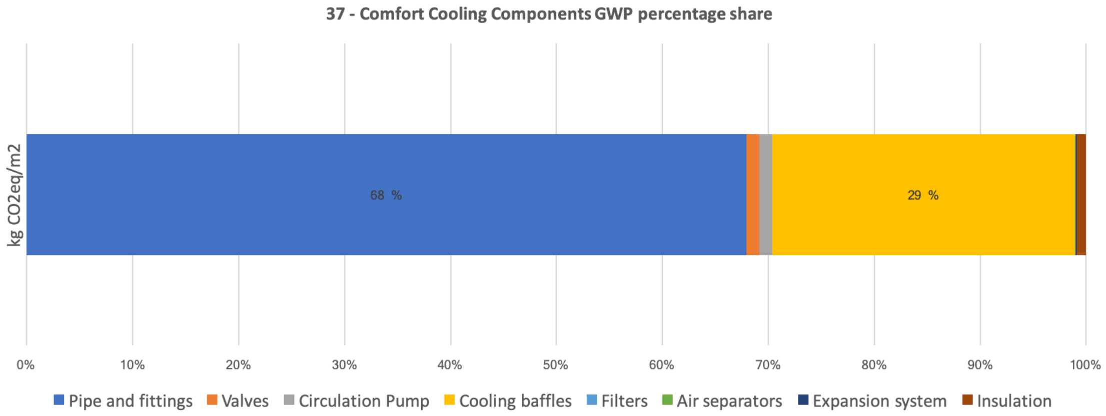


Figure 12: GWP percentage share of the included comfort cooling components for the assessed lifecycle stages (A1-A3, A5-A4, B4, C1-C4)

Table 9: Contribution of the comfort cooling components to the overall GWP for the assessed life cycle stages (A1-A3, A4-A5, B4, C1-C4) - calculated with generic data

Component	**Amount**	**Unit**	**GWP** ($kgCO_2eq/m^2$)
Pipe and fittings	13350	kg	18,174
Valves	418	p	0,325
Circulation Pump	7	p	0,323
Cooling coils	86	p	7,637
Filters	1	p	0,006
Air separators	1	p	0,007
Expansion system	1	p	0,046
Insulation	546	m^2	0,412
Total			26,748

6.3.4 41, 43, 44 & 49 - Electrical Installations

Electrical installations are the building element group that has the second-highest contribution to the total GWP. With a total impact of 74,047 $kgCO_2eq/m^2$, they are roughly 28% more impact intensive than the heating and comfort cooling system combined.

The PV panels, electric cables and light fixtures are the most emission intense components, with a GWP of 25,094, 23,740 and 23,159 $kgCO_2eq/m^2$ respectively (Table 18). It should be noted that after ventilation ducts and supply/extract air units, these are the most emission-intensive components of all the investigated technical installations. As shown in Figure 13, the emergency lights contribute only 2% to the total GWP from electrical installations, while the cable carrying system has negligible impact.

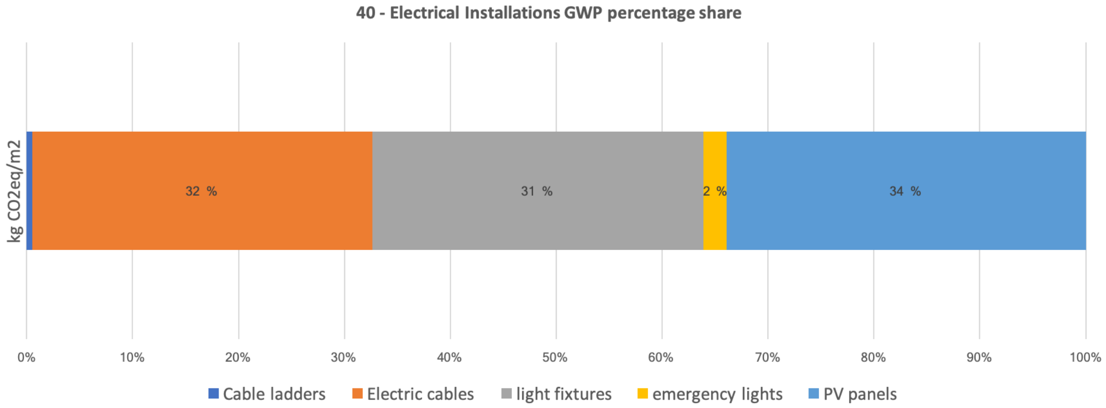


Figure 13: GWP percentage share of the included electrical installation components for the assessed lifecycle stages (A1-A3, A5-A4, B4, C1-C4) - calculated with generic data

Table 10: Contribution of the electrical installation components to the overall GWP for the assessed life cycle stages (A1-A3, A4-A5, B4, C1-C4) - calculated with generic data

Component	**Amount**	**Unit**	**GWP** ($kgCO_2eq/m^2$)
Cable ladders	216	kg	0,413
Electric cables	20692	kg	23,740
light fixtures	2066	p	23,159
emergency lights	287	p	3,282
PV panels	500	m^2	25,094
Total			74,047

6.4 Comparison of results using generic and EPD data sources

In the following section, results from the second life cycle assessment using EPD data are presented in comparison to results from the primary assessment using generic data. Results for technical installations percentage share of total embodied carbon emissions and component groups from the EPD LCA model are included in Appendix 10.

The percentage share of each life cycle phase is relatively similar between the two assessments, as can be seen from Figure 14. The construction phase (A4-A5) shows a slightly higher relative contribution for the analysis using EPD data. Also, the end-of-life stage has a slightly higher relative contribution for the EPD data than the generic, as can be seen from Figure 15.

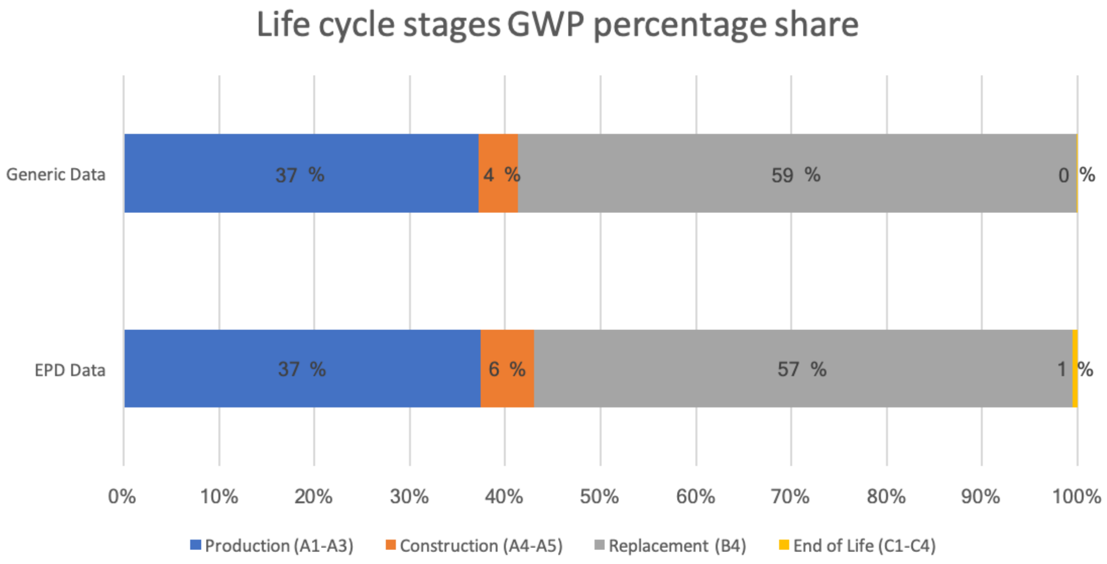


Figure 14: Life cycle stages GWP percentage share of total embodied emissions from technical installations

As shown in Figure 15, the general trend for the 3-digit building elements included in this study is that the impact intensity from the analysis using EPD and product specific data is lower than that of the analysis using generic data. The average decrease in emission intensity per 3-digit building element is 2 $kgCO_2eq/m^2$. The largest difference in the results are for building element 364 with a decrease in GWP of 29,795 $kgCO_2eq/m^2$ of which supply and extract air units make up 26,667 $kgCO_2eq/m^2$, followed by 362 (ventilation ducts), 433 (electric cables) and 442 (light fixtures) with a reduction of 13,719 $kgCO_2eq/m^2$, 13,514 $kgCO_2eq/m^2$ and 12,612 $kgCO_2eq/m^2$ respectively.

Exceptions to this trend are 3-digit building elements 324 and 374 (valves for heating and cooling systems) and 376 (insulation for comfort cooling installations). These building elements show an increase in GWP of 0,015 and 0,033 $kgCO_2eq/m^2$ for the heating and cooling valves respectively and a GWP increase of 0,384 $kgCO_2eq/m^2$ for the comfort cooling insulation. Also, the AHUs and intake/exshaust fans show an increase in GWP of 1,970 and 0,073 $kgCO_2eq/m^2$ respectively, compared to the main analysis with generic data.

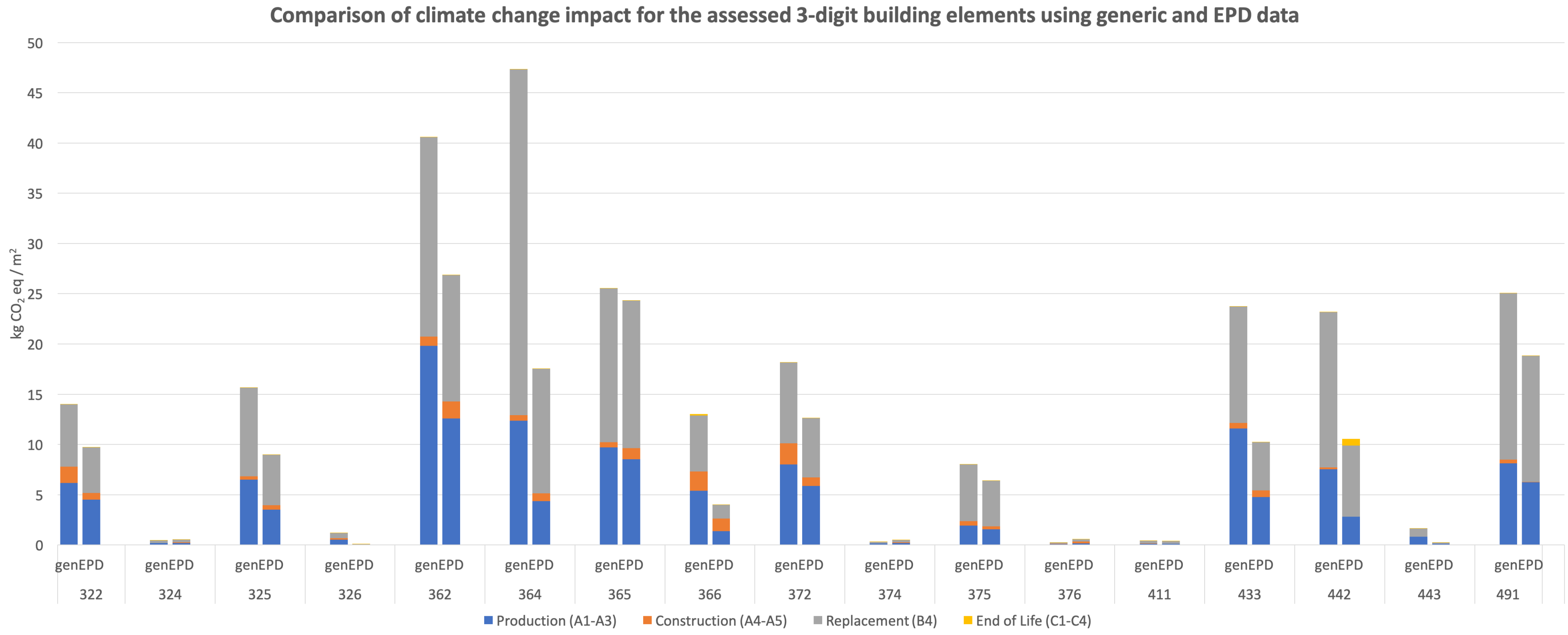


Figure 15: Comparison of climate change impact for the assessed building elements in $kgCO_2eq/m^2$ using generic and EPD data

6.5 Sensitivity Analysis

In the following section, results from the sensitivity analysis are presented. Based on results from the two inventory structure methodologies, it was considered appropriate to study in greater detail circular ducts and supply/extract air units from 3-digit building elements 362 and 364, in addition to 433 (electric cables) and 442 (light fixtures).

6.5.1 Uncertainty of Material Quantities

There is a certain level of parameter uncertainty related to the material composition and quantity of the included components in the life cycle inventory. These values may vary depending on the specific datasheet or EPD used to extrapolate weights and/or material composition. As an example of this, Table 11 shows the variability of ventilation duct weight per meter. Since the datasheets used by Alexander Borg to extrapolate the duct and fitting weights from HVL Bergen was Kruge, the same weights were used for estimating duct weights in this study so that the conversion factor was used to estimate duct equipment should be as precise as possible. The sensitivity of the results in regards to which manufactur weight is chosen is given in Figure 16. The impact is slightly higher from Lindab compared to ventistål with emission intensities of 16,383 and 16,395 $kgCO_2/m^2$, while Kruge results in an impact of 19,066 $kgCO_2/m^2$ for the generic data. The standard deviation is 1,546 for the generic data, 0,858 for the EPD data, and 0,687 for the difference between the two methodical variations of inventory structure (i.e., generic and EPD).

Table 11: Variation in weight per meter for circular ventilation ducts depending on the manufacturer

Manufacturer	Size [mm]	Weight [kg/m]
Ventistål	ø630	12,2
Lindab	ø630	12
Kruge	ø630	14,3
Ventistål	ø800	15,4
Lindab	ø800	17,4
Kruge	ø800	18,2
Ventistål	ø1000	25,5
Lindab	ø1000	24,1
Kruge	ø1000	25,7

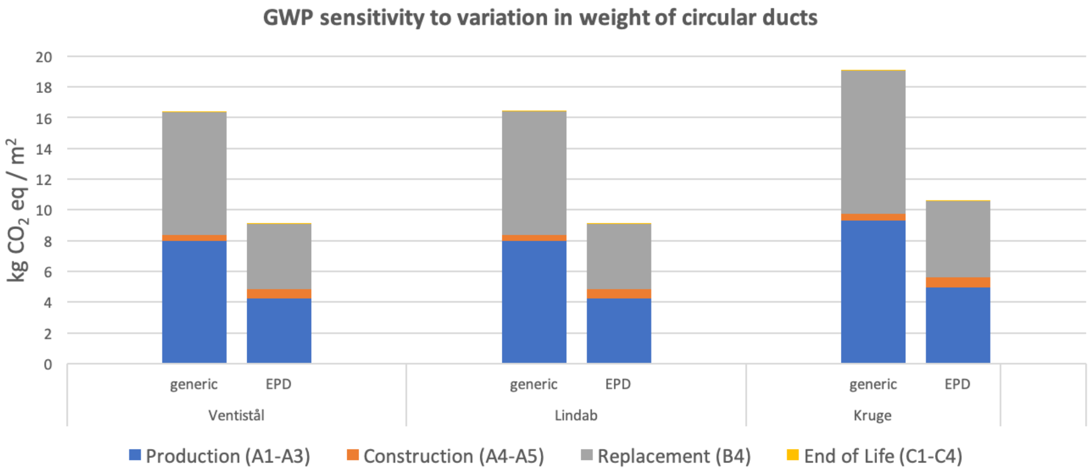


Figure 16: Result sensitivity to duct weight variability of circular ducts from different manufacturers - GWP from circular ducts

6.5.2 Variability Between Objects Modelled by Procedure 2

Electricity cables and light fixtures are among the investigated components that show the most considerable difference between the two model results. They are both modelled according to procedure 2, described in section 5.3, and the following subsection presents the model result sensitivity to the available choices of objects for both generic and product-specific data for these components. The columns labeled reference is the alternative used in the two LCA variations conducted in this thesis and is the same as in the results presented in the sections above.

Figure 17 shows the difference in impact intensities for different component alternatives in the OneClick LCA database. The variation of emission intensities is the largest for the generic data, with an average GWP of 20,142 $kgCO_2/m^2$ and a standard deviation of 3,021. For the product-specific data, the variation is lower, and the average GWP is 9,035 $kgCO_2/m^2$ with a standard deviation of 0,460. Lastly, the average difference between the generic and EPD data is 11,107 $kgCO_2/m^2$ with a standard deviation of 2,790.

Similarly, Figure 18 shows the variation in impact intensities for light fixtures. As seen from the graph, there is a much larger variation for both model results than for the electricity cables. For the generic data, the average GWP is 37,955 $kgCO_2/m^2$, with a standard deviation of 17,069, while the EPD data has an impact intensity average of 11,364 $kgCO_2/m^2$ with a standard deviation of 3,023. Interestingly, the standard deviation in the EPD data for light fixtures is of the same significance as the generic data for electricity cables. The average difference between the two LCA variations is 26,591 $kgCO_2/m^2$ with a standard deviation of 15,824.

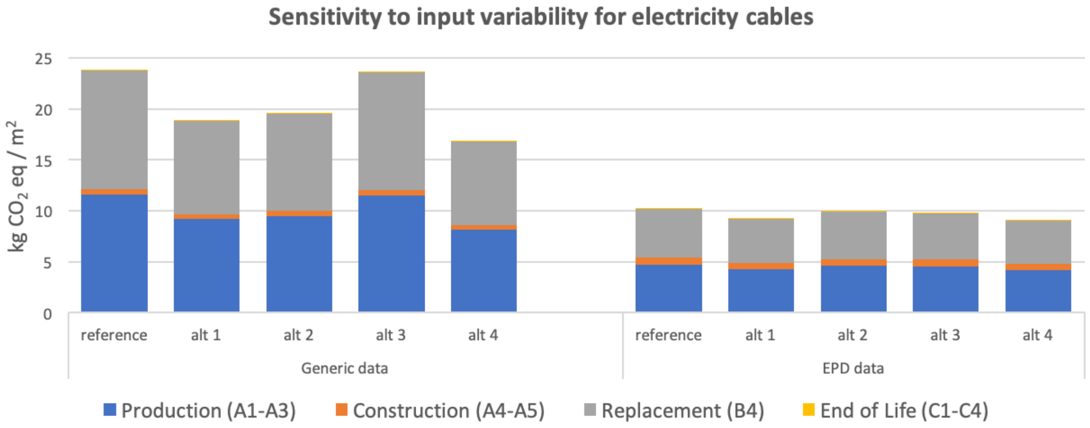


Figure 17: Model result sensitivity to input variability of electricity cables from the OneClick LCA database

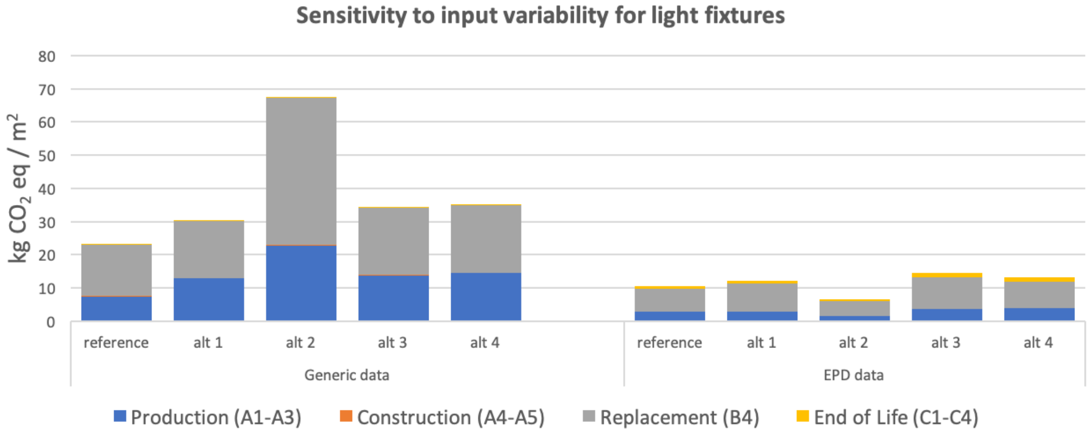


Figure 18: Model result sensitivity to input variability of light fixtures from the OneClick LCA database

6.5.3 Uncertainty from Modelling Procedure 3, Variability in Material Emissions and Result Sensitivity

As the results presented in section 6.1 and 6.4 show, the 3-digit building element group with the highest impact intensity for the generic model, as well as the most significant difference between the generic and product-specific model results is 364, equipment for air distribution. In section 6.3 it was established that the main contributor to this high impact intensity is the supply and extract air units. Therefore, this section presents some of the uncertainty relating to the supply and extract air units, with a primary focus on model result sensitivity relating to modeling procedure 3.

In the generic data LCA model, the supply and extract air units are modelled according to procedure 2, while in the EPD data LCA model, they are modelled according to procedure 3. Figure 19 shows the resulting GWP impact from supply and exhaust air units when modelled according to procedure 2 (left colum) compared to procedure 3 (middle and right colum) calculated with generic and EPD data. The right and left columns are the same impacts as presented in Figure 15, while the middle column is calculated using the same input materials as all other ventilation components modelled with procedure 3. When switching from modelling procedure 2 to 3, the impact intensity is reduced from 40,173 $kgCO_2/m^2$ to 23,039 $kgCO_2/m^2$ for the generic data model.

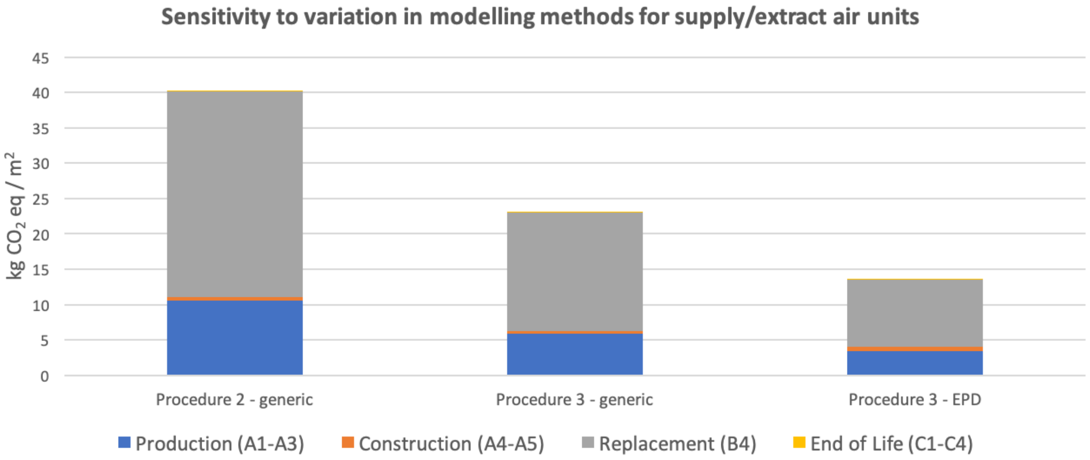


Figure 19: Result sensitivity to modelling procedure 2 and 3 for supply and extract air units

As described in section 5.3, modeling procedure 3 is based on modeling a component as the individual materials and respective quantities that the component is made of and is used when there are no equivalent or similar components available in the OneClick LCA database. There is a considerable selection of input options for each material, and the variability or spread in the emission factors for each material is significant. Figure 20 shows a sample of the emission factor variation for the most common material types in this study for modeling procedure 3. The samples taken from the OneClick LCA database include the entire range of emission intensities for the given material and are arranged from least to most emission-intensive. Table 12 shows the average emission intensity and standard deviation for 1 kg of each material.

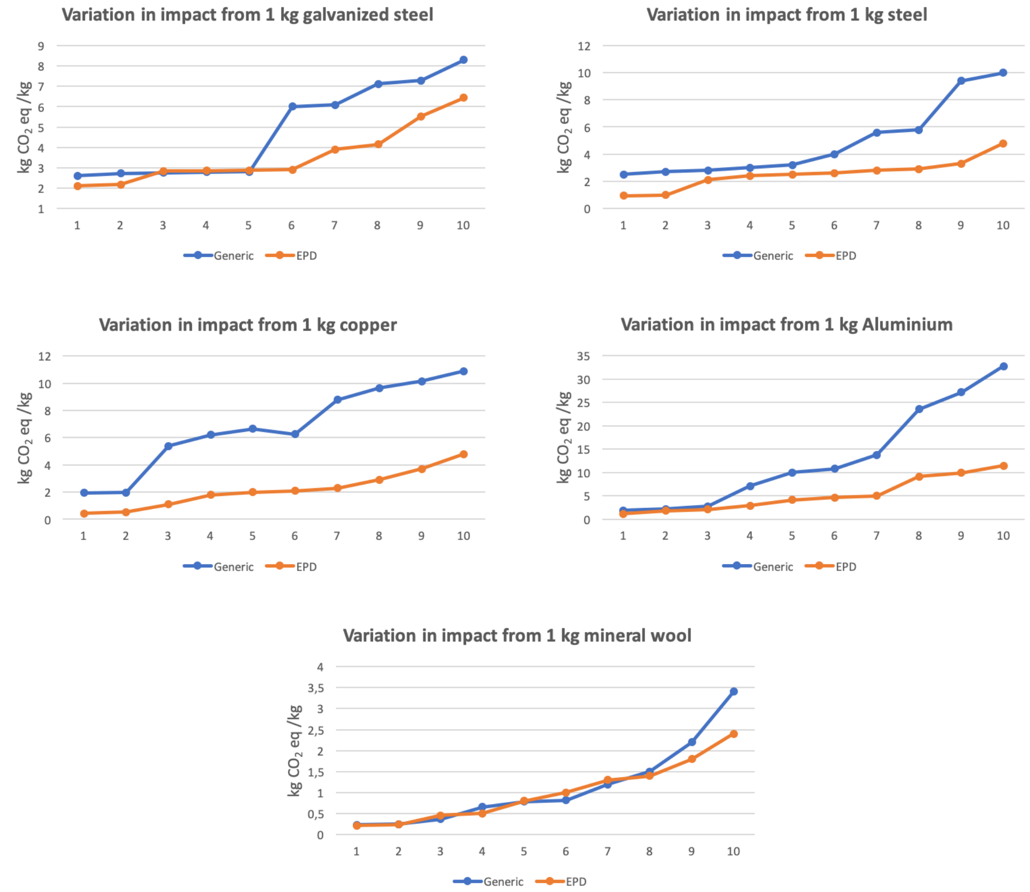


Figure 20: Variability in emission factors from 1 kg material for the most used materials in modelling procedure 3

Table 12: Average ($\overline{x}$) values and standard deviation (σ) for emission variability of 1 kg material from different options in the OneClick LCA database

Material		$\overline{x}$	σ
Galvanized steel	Generic	4,848	2,313
	EPD	3,581	1,436
Steel	Generic	4,9	2,786
	EPD	2,533	1,109
Copper	Generic	6,781	3,148
	EPD	2,165	1,369
Aluminium	Generic	13,179	11,047
	EPD	5,219	3,671
Mineral wool	Generic	1,142	1,002
	EPD	1,013	0,715

In order to investigate the result sensitivity to emission variability in materials when using procedure 3, supply and extract air units are modelled using different material input data from the OneClick LCA database. Figure 21 shows the minimum and maximum GWP impact from the supply and extract air units based on different material choices, as well as reference values. The reference values are calculated with the same material choices as all components modelled according to procedure 3 in the two main LCA models, meaning the EPD reference pole in the graph shows the same impact as in Figure 15 and 19. The generic reference pole is also the same as in Figure 19. The minimum impact intensity is 9,324 and 7,484 $kgCO_2/m^2$ for generic and EPD data sources respectively, and the maximum impact intensity is 30,132 and 21,615 $kgCO_2/m^2$.

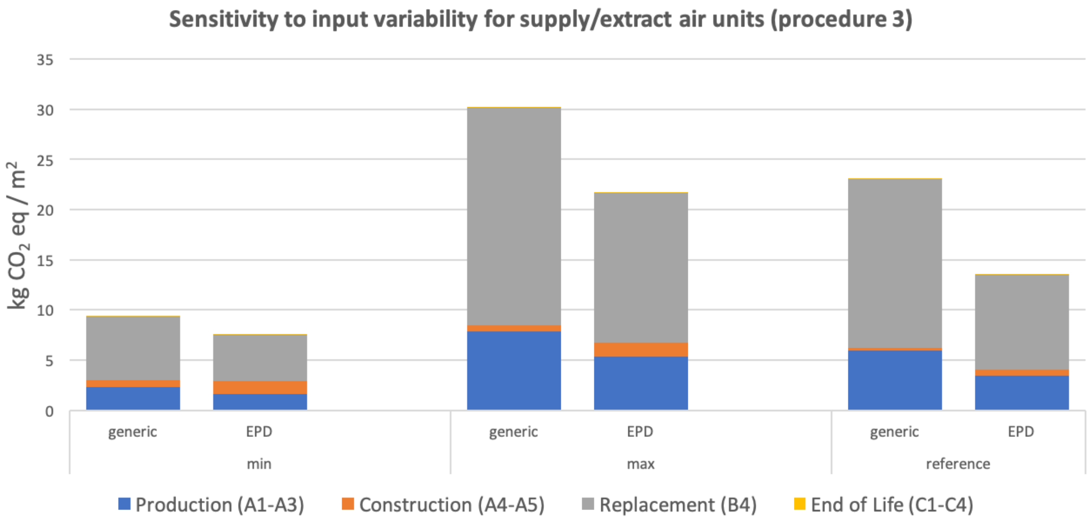


Figure 21: Result sensitivity to material input variability - minimum and maximum emission intensity from supply and extract air units modelled with procedure 3

7 Discussion

In this section, the results from the LCIA are discussed in further detail. First, the main findings regarding the second and third research questions are discussed, followed by the most emission-intense components. The results are compared to other studies found in the literature review, and differences between the modeling procedures and other uncertainties are discussed.

8 Discussion

In this section, results from the LCIA are discussed in further detail. First, the main findings regarding the second and third research questions are discussed. Then sensitivity from the different modeling procedures is discussed, and results are compared to findings from other studies in the literature review. Lastly, other possible errors and uncertainties are discussed.

8.1 Main Findings

8.1.1 The Embodied Impacts of Technical Installations in wing A of OSC

The results from the LCIA indicate that the embodied impact from technical installations is significant. This becomes even more apparent when comparing the impacts to the rest of the building, as they constitute 33%-46% of total embodied carbon. When the operational energy throughout the building's use phase is included, the contribution from material content of the technical installations is 19-29% of the total emissions throughout the building's lifetime. The ventilation system has the most significant impact compared to the heating, comfort cooling, and electrical installations and makes up almost 50% of the embodied GHG emissions. This to be expected, at least compared to the other parts of the HVAC systems, and can be largely explained by extensive material quantities utilized for the ventilation system.

Due to the short lifetime of various components as compared to that of the building structure, replacement of equipment during the use phase (B4) is the most emission intense module of the entire life cycle, followed by production (A1-A3). The construction phase is found to have a relatively small yet significant impact (4-6%) compared to the previously mentioned modules. This differs from what is found in other studies (Ylmén et al., 2019) and is possibly due to different components and materials in the investigated installations. Another explanation is that emissions from the construction site might be overestimated in this study, as is further discussed in section 8.4. Impacts related to the end-of-life phase is are found to be negligible, with the exception of light fixtures in the EPD data model. However, no conclusion can be made as to why more significant emissions are associated with the end-of-life phase for the product-specific light fixtures based on the results in this study.

8.1.2 The effect of Environmental Product Declarations for Technical Installations

Comparison of the two variations of inventory structure methodology indicates that the emission impact of technical installations can be drastically reduced by going from generic to product-specific values. The results from the case study show that impact emissions are reduced by 41% when switching from generic to EPD data sources. However, as the sensitivity analysis demonstrates, there can be considerable variation between similar components or materials for both the generic and EPD data sources. Thus some uncertainty is associated with these results. Still, there is a clear trend that GHG emissions are lower for EPD data. The reduction in impact for product-specific data is most likely due to increased focus on sustainability from manufacturers. The required detailed environmental assessment in the development of EPDs enables the identification of hotspots in the product life-cycle and thus the opportunity to improve environmental properties.

Depending on the specific assumption, or choice of input data in OneClick LCA, the difference between two equivalent materials or components can vary greatly, even if both are from generic or product-specific data sources. This raises the question of whether differences in production technology alone cause the difference in emission impact or if other factors such as different background data used to calculate whole life emissions affect the resulting environmental impacts. If the latter is correct, a solution could be that it is required, for example, by the PCR, that a single and harmonized background database is used to calculate material emissions. Then, the remaining variability would be caused only by differences in actual environmental performances between manufacturers.

8.1.3 Contribution from Different Components

The results show that 11 of the investigated components make up 90 % of the total embodied impact of the case study. To a large degree, the impact intensities are proportional to the material amounts and weight of the given components. Exceptions to this are the AHUs, heat pumps, and light fixtures, which have relatively large contribution shares compared to weight.

As expected, the ventilation ducts and fittings have the highest impact intensity of all components. This is due to the extensive material amounts of galvanized steel used in the production ducts. The emissions are reduced by 33% from the generic to the EPD results. The uncertainty related to the ducts is relatively small and is in any case equal between the two models. Therefore the ducts show one of the most reliable results regarding the difference between generic and EPD data. The pipes from the heating and cooling network also have high embodied emissions. The availability of data is slightly better than for ducts, but also where improvements are needed.

Supply and extract air devices are the second-largest GHG contributor of all the component groups. As stated in section 5.3, there are many different types of this component included in the inventory, and the most emission-intensive is the VAV supply air devices. There was only one component input option with equivalent function for generic data in the OneClick LCA database and none for product-specific, meaning it was modelled according to procedure 3. This means that there is some uncertainty related to the results for this component, and more research is needed to determine the embodied impact of these devices. However, the results of this study, combined with the lack of available data, points to VAV supply air units as one of the most critical components to develop EPDs for.

The silencers, cooling baffles, and radiators all have GHG impacts of similar magnitude, ranging from 7,6-8,6 $kgCO_2eq/m^2yr$ in the generic model and 4,3-5,4 $kgCO_2eq/m^2yr$ in the EPD model. There were no environmental data available for silencers or cooling baffles in the generic or product-specific database, putting them at high priority for EPD development based on the same argumentation as for VAV supply air units. Radiators had several options for both data sources, however, these are almost exclusively from French EPD programs. It would be interesting to see product-specific data from Nordic production to see if this affects the environmental properties.

Of the electric installations investigated in this study, results indicate that almost all the embodied emissions come from the PV panels, electric cables, and light fixtures. The latter two show significant impact reductions when modelled with EPD data, while the PV panels, although reduced, still show a high impact intensity. These components had the most environmental data options available for both generic and product-specific in the OneClick LCA database of all the components included in this study. While this increases the prospect of finding a more exact match for the component, it can still mean significant variability of the input data, as seen in section 6.5.2. However, the general order of magnitude of the GHG emissions is still deemed accurate. It should be noted that despite data availability being better for these components than others, it was still found to be minimal, especially for light fixtures.

The fact that the quantity of electric cables is based on an average per GFA and not building-specific data also implies larger uncertainty of their actual impact as the material quantity may be under-or overestimated. However, including them in this fashion will give a more accurate representation of the embodied impacts from electrical installations than not including them. Still, no reliable conclusions regarding their actual impact share can be made from this study.

8.2 Variability from Differing Modeling Procedure of Components

It is evident that the three different procedures used for modeling the inventory in OneClick LCA have varying accuracy for estimating the embodied impacts of components. Procedure 1 will, in principle, give the most accurate presentation of actual material impact and process-related emissions in the production of a given component. However, due to the general lack of data for technical installations, few components were modelled using this procedure.

Procedure 2 is assumed to be the second most accurate, as it will most likely capture embodied emissions from the production of the specific component better than procedure 3. Additionally, adjustments such as modelling the component based on weight taken from datasheets instead of unit quantities are made to capture the correct material impact more precisely. Figure 17 and 18, show the sensitivity to different input choices for two of the components modelled after procedure 2. As the results show, the variation is generally larger for generic data. While the impacts from these components cannot be established with great certainty, the results still indicate the magnitude of emission impacts associated with the given component. The EPD data is much more consistent than the generic, and results show less sensitivity to different input options. However, the sensitivity of different input options can vary from component to component, and it cannot be excluded that difference between generic and EPD data can be both under-or overestimated. Still, the general trends indicate that EPD data is consistently lower, and sensitivity to potential differences should not deviate from the general conclusion that product-specific data reduce the impacts.

On the other hand, there are some cases where the results from the generic model give a lower GWP impact than for the EPD model. Specifically, this is true for the valves, AHUs, and insulation for the comfort cooling network. In the case of the valves, where some of the valves are modelled according to procedure 1 and others 2, some of the valves are motor-controlled, and no such options are available in the generic database while it is for product-specific data. Therefore, the likely reason for the difference is the availability of the type of valves in the generic and EPD databases. Regarding the AHUs, the available choices are much worse for the EPD database, and it was challenging to find an option with the same characteristics. The most appropriate option was chosen; however, the differences in environmental impact between the generic and product-specific AHUs could be caused by the fact that they may have larger differences in technology. For the insulation, it was modelled according to procedure 1 for both the generic and EPD model. The deviation, in this case, is unknown but could be caused by underestimation of emissions in the generic case or simply differences in environmental performances between the manufacturers as the generic are based on a French average, and the product-specific is an EPD from GLAVA.

Procedure 3 is the method with the most uncertainty. Based on the results from the sensitivity analysis (Figure 19, it is reasonable to assume that emissions could be significantly underestimated with this method. This is supported by the results in Figure 21, which shows the maximum impact from the supply and extract air units when modelled with procedure 3 is still approximately 10 $kgCO_2eq/m^2$ lower than when modelled with procedure 2. This could partly be because emissions generated as a consequence of the specific product's production are not captured accurately and partly because elements of the components, such as control devices for VAV supply air units and VAV dampers, are not included. To compensate, all galvanized steel in ventilation components modelled according to procedure 3 is modelled as ventilation ducting, as this is assumed to more correctly capture emissions from the manufacturing process. The difference in accuracy will, of course, vary between components and is likely more correct for silencers, which do not include any electrical elements, than for VAV dampers or VAV supply air units.

While procedure 2 and 3 does imply more uncertainty regarding the LCIA results for both models, it is not easy to establish whether the embodied impact of the technical installations are over or underestimated. Either way, it still does not affect the conclusions of the second research question in this study that the embodied impacts of the technical installations are in no way insignificant. In regards to the third research question, however, the lack of environmental data availability on technical installations is in of itself an important finding and highlights the need for more EPDs for these components in general.

8.3 Agreement with Literature

A direct and meaningful comparison between results from this study with studies previously described in the literature is hampered by the fact that these target different buildings, system boundaries and employ different method choices. E.g., most previous studies either analyze a whole building, or if focused on technical installations, include only HVAC systems or ventilation systems. However, it is still considered beneficial to compare different parts of the current analysis to studies reported in the literature to lend credibility to the results.

The study by Kiamili et al. (2020) on the embodied carbon of HVAC systems for an office building in Switzerland is comparable to the results for the ventilation, heating, and comfort cooling system assessed in this study. The study has the same functional unit over the same building lifetime. While the included life cycle modules are slightly different(A4-A5 and C1 are excluded), it may still provide a useful comparison. The total impact of the HVAC systems in the Swiss office building is 183 $kgCO_2eq/m^2$, which coincides well with this case where the embodied impact for the ventilation, heating, and comfort cooling system is 184,6 $kgCO_2eq/m^2$ in the generic model.

With regards to the electrical system, the most comparable study is the analysis of embodied carbon of mechanical, electrical, plumbing, and tenant improvements by Rodriguez et al. (2020). The electrical systems assessed in this study included generators, batteries, electrical service and distribution, wiring devices, and lighting fixtures. The study by Rodriguez et al. (2020) is limited to modules A1-A3 and assesses hypothetical building models representing typical commercial office buildings in the Pacific North West. The embodied carbon of the electrical system is found to be approximately 0,17 $kgCO_2eq/m^2yr$ for high performance buildings with size ranging from 1858-27870 m^2, and approximately 0,27 $kgCO_2eq/m^2yr$ for building sizes ranging from 929-7432 m^2. When excluding the PV system in this study, the embodied impact from A1-A3 is 0,33 $kgCO_2eq/m^2yr$, which is almost twice as high as the larger building size from analysis by Rodriguez et al. The embodied impact is more comparable to the smaller building size from the study, although the GFA of the OSC falls just outside this size range. The electrical systems included in the study are of a larger precision than here, and one should therefore expect the impacts to be higher. The higher impact found here could be explained by different buildings and that the analysis is based on hypothetical buildings, but the credibility of the high impacts cables and light fixtures found in this study is still decreased. However, Rodriguez et al. (2020) does find that light fixtures are among the most emission-intense components for mechanical, electrical, and plumbing systems, indicating that while the impact might be overestimated in this study, they still have a high impact.

8.4 Possible Uncertainties and Errors

Uncertainties and unknowns are inevitable in any study, especially for complex life cycle assessments consisting of many parts and various factors that influence results. In addition to the sensitivity analysis and uncertainty already discussed, some other possible errors or unknowns might influence the precision of the results in specific ways.

The emission impacts related to waste on the construction site, installation process, in addition to demolition, transport, waste processing, and disposal from the end-of-life stage, were all calculated from the default settings in OneClick LCA since no other information was available. The uncertainty related to these calculations is unknown. Furthermore, emissions from the construction site, as described in section 5.5, are based on average emissions per m^2 GFA for the given fuel scenario. Since the scope of this study only includes technical installations and the emissions in this scenario are based on the construction of the entire building, the emissions from the construction site (A4-A5) are likely overestimated. However, since the impact of construction and end-of-life is minor compared to total impact, uncertainties in these processes will not shift the total picture very much.

The results are only as accurate as the inventory data. In this study, several assumptions are made to include as many technical installations as possible; thus, parameter uncertainty is inevitable. Elements such as insulation for the HVAC systems were not included in the IFC files and are instead based on planning documents. Therefore assumptions are made on the type and thickness of insulation. Also, since no inventory data on the heating and comfort cooling systems for OSC was provided, quantities and component types from these systems and equipment for air distribution in the ventilation system are estimated based on extractions from HVL Bergen IFC files. While these assumptions may lead to inaccurate representation of component data, it is deemed more accurate than leaving them out.

Several parts of the technical installations are excluded from this study. The ventilation system in the presented study is demand-controlled through a VAV control system. Only parts of the system directly connected to ventilation ducts, such as fire and flow dampers and VAV supply air units, are included in the study. Additional electronic components such as control systems, room sensors, motors, meters, etc., were not available, and a detailed assessment of these elements could therefore not be performed. Overall, the availability of information on the electrical installations was scarce. Components such as electrical distribution boards including circuits, fuse links, bus bars, residual current detectors, and bypass equipment are therefore excluded., An assessment with higher inventory resolution, including all electronic equipment, may give a more accurate estimate of the actual contributions of technical installations and further increase the relative importance of embodied emissions.

Finally, this study only assesses the environmental impact concerning climate change. As discussed in section 4.1.5 of the literature review, technical installations are found to have significant importance for environmental impact categories other than GWP. While the exclusion of other impact categories does not undermine the findings of this study, they should be considered to form a complete picture of the environmental impacts of technical installations and avoid problem shifting.

9 Conclusion

This study has investigated the embodied impacts associated with technical installations in modern energy-efficient buildings. While the LCA study conducted here only represents data from a single building, combining these results with findings from other literature studies nevertheless allows for some general conclusions to be drawn. In particularly those that apply to technical installations and HVAC systems.

Findings from the literature review indicate the material part of technical installation is often inadequately addressed, and that there is a need for better resolution in terms of components, material composition and dimension. The results with regards to the contribution of embodied emissions from technical installations varies considerably between different studies. However, in more recent studies where considerable efforts are made to develop more detailed and complete inventories, higher impact from the embodied materials of technical installations are reported. Results from the LCA conducted in this study, further reinforce these findings.

For the investigated life cycle phases, the manufacturing process of components and replacement are shown to have the largest impact overall, accounting for 37% and 57-59% of the total GWP for the technical installations. Installation and transport during the construction phase have minor, but significant impact (4-6%), while impacts from the end-of-life phase are negligible. The results show that the embodied impact of technical installations contributes 33-46% of the building's total embodied impact, and 19-29% when operational energy use is included. These findings highlight the importance of embodied emissions in the material content of technical installations regarding environmental impact mitigation of buildings.

The absence of comprehensive life cycle inventories found in literature, in addition to lack of environmental data availability in the database used for this study, is also reflected in the lack of EPDs for HVAC systems especially. Developing more EPDs for technical installations may allow manufacturers to identify hotspots in the product's life cycle, thus providing opportunities to improve the environmental performance of products. Additionally, it can empower designers to perform product comparisons and facilitate environmentally conscious decisions. The results of this study point to VAV supply air units, air handling units, ventilation ducts, and piping for heating and cooling systems as the most critical places for improvement, followed by heat pumps, cooling baffles, and duct silencers. However, more detailed research is needed to determine the true environmental impact of specific components and different types of HVAC systems.

10 Future Work

Based on findings in the literature review and the conducted study in this thesis, there several recommendations for further work.

First, the findings in this study are limited to Global Warming Potential, and more environmental impact categories need to be assessed to fully evaluate all the embodied environmental impacts of technical installations and avoid problem shifting. Secondly, as discussed in section 8.4, an assessment that includes all the electronic components of the HVAC system is needed to reveal its true impact. More research is also needed to determine the impact of different kinds of ventilation, heating, and cooling systems.

Regarding electrical installations, a more detailed inventory with better resolution than what was included in this study is needed to evaluate the embodied impacts of electrical power installations in buildings. This includes more accurate inventory data for the same components assessed in this study to verify their impact, in addition to a more complete inventory to understand the full impacts of electrical installations in buildings.

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Appendix

Quantity Extractions From HVL Bergen

Table 13: Amount of each component group, categorized according to the table of building elements, extracted from the HVL ventilation IFC file

3-digit	Building Element	Component Group	Amount	Unit	Unit/GFA
362	Duct network for air treatment	Circular ducts	6456	kg	2,89
		Rectangular ducts	2214	kg	0,99
		Duct fittings	2013	kg	0,90
364	Equipment for air distribution	VAV dampers	60	stk	0,03
		VAV Supply air units	63	stk	0,03
		Supply air valves	79	stk	0,04
		Exhaust valves	72	stk	0,03
		Shutters	2	stk	
365	Air treatment equipment	Air Handling Units	1	stk	
		Silencers	150	stk	0,07

Table 14: Amount of each component group, categorized according to the table of building elements, extracted from the HVL pipe IFC file.

3-digit	Building Element	Component Group	Amount	Unit	Unit/GFA
322	Water mains	Galvanized steel pipes	14047	kg	0,97
		PEX	0	kg	
		Fittings	2107	kg	0,15
324	Fittings for heating installations	Ball valves	656	p	0,05
		Balancing valves	9	p	0,00
		Thermostat-controlled radiator valve	86	p	0,01
		Radiator control valve	243	p	0,02
			994		0,07
325	Equipment for heating installations	Pumps	14	p	0,00
		Radiators	272	p	0,02
		Filters	1	p	
		Air separators	1	p	
		Expansion system	1	p	
372	Pipe network for comfort cooling	Galvanized steel pipes	18272	kg	1,27
		PEX	0	kg	
		Fittings	2741	kg	0,19
374	Fittings for comfort cooling	Ball valves	324	p	0,02
		Butterfly valves	10	p	0,00
		Balancing valves	172	p	0,01
		Thermostat-controlled radiator valve	146	p	0,01
		Two-way valves cooling coil	7	p	0,00
375	Equipment for comfort cooling	pumps	11	p	0,00
		cooling baffles	135	p	0,01
		Filters	1	p	0,00
		Air separators	1	p	0,00
		Expansion system	1	p	0,00

LCA Results from the EPD data model

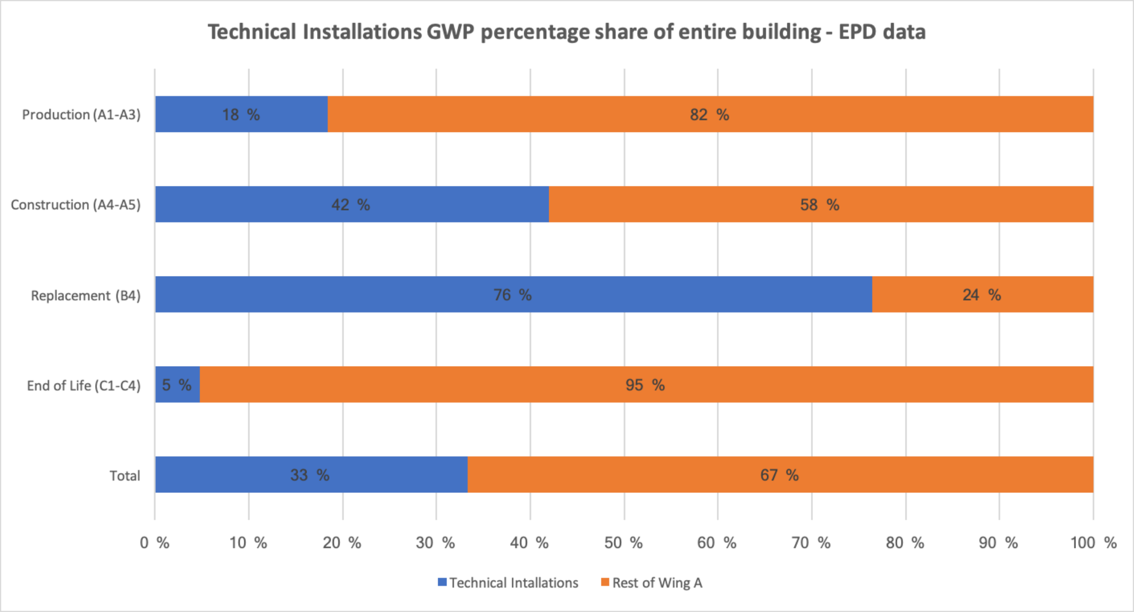

Figure 22: Technical Installations GWP percentage share of the total embodied emissions from wing A - calculated with EPD data

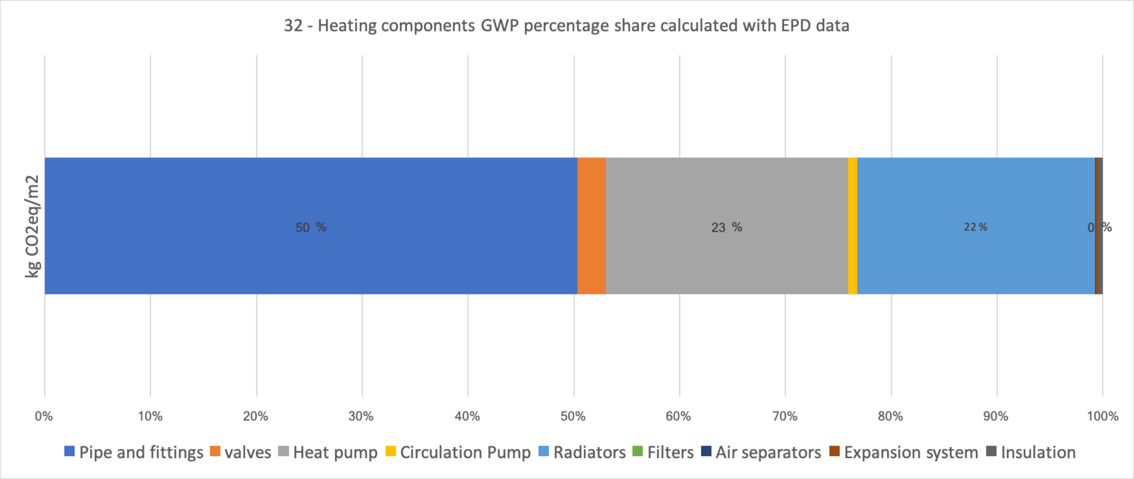

Figure 23: GWP percentage share of the included heating components for the assessed lifecycle stages (A1-A3, A5-A4, B4, C1-C4)- calculated with EPD data

Table 15: Contribution of the heating components to the overall GWP for the assessed life cycle stages (A1-A3, A4-A5, B4, C1-C4)- calculated with EPD data

Component	**Amount**	**Unit**	**GWP** ($kgCO_2eq/m^2$)
Pipe and fittings	10264	kg	9,703
valves	632	p	0,526
Heat pump	3	p	4,416
Circulation Pump	9	p	0,165
Radiators	173	p	4,334
Filters	1	p	0,001
Air separators	1	p	0,007
Expansion system	1	p	0,046
Insulation	519	m^2	0,089
Total			19,287

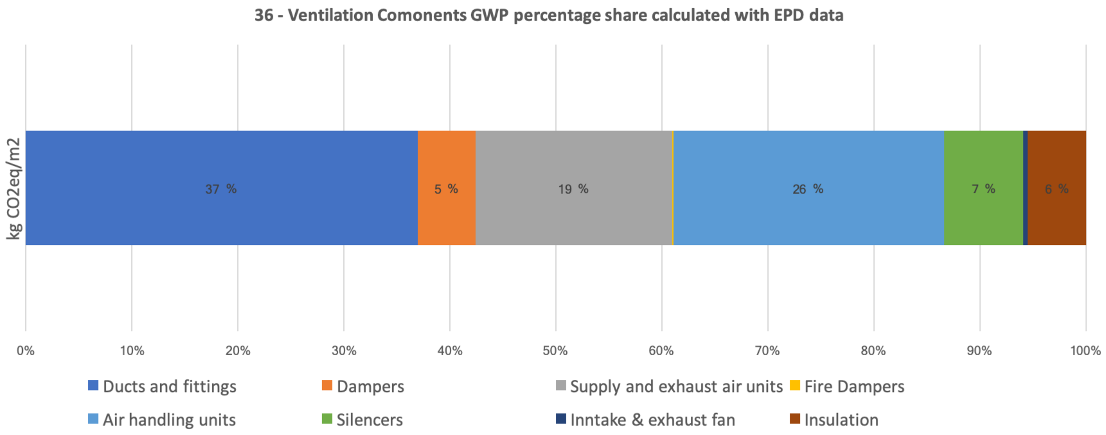

Figure 24: GWP percentage share of the included ventilation components for the assessed lifecycle stages (A1-A3, A5-A4, B4, C1-C4)- calculated with EPD data

Table 16: Contribution of the ventilation components to the overall GWP for the assessed life cycle stages (A1-A3, A4-A5, B4, C1-C4)- calculated with EPD data

Component	**Amount**	**Unit**	**GWP** ($kgCO_2eq/m^2$)
Ventilation ducts	24065	kg	26,877
Dampers	246	p	3,955
Supply/extract air units	540	p	13,504
Fire Dampers	7	p	0,073
Air Handling Units	7	p	18,761
Silencers	368	p	5,466
Inntake/extract fan	4	p	0,309
Insulation	2645	m^2	4,007
Total			72,932

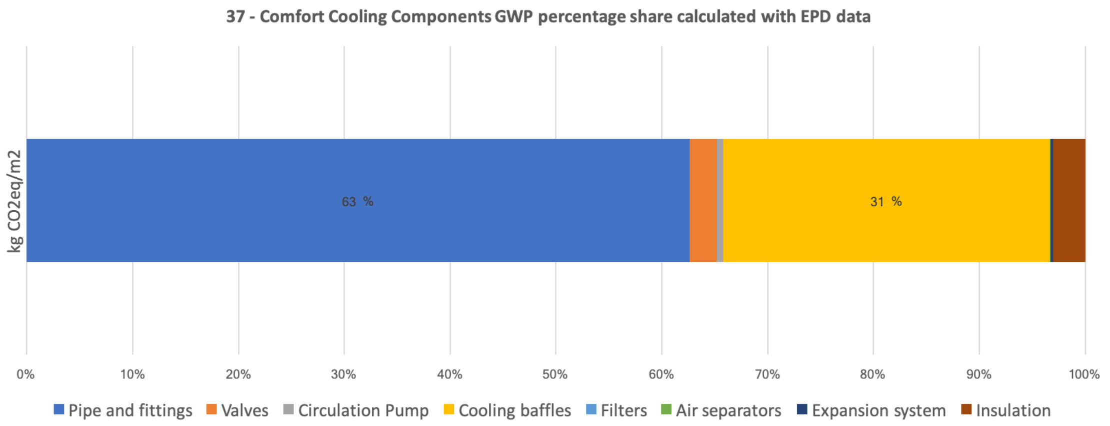

Figure 25: GWP percentage share of the included comfort cooling components for the assessed lifecycle stages (A1-A3, A5-A4, B4, C1-C4)- calculated with generic data

Table 17: Contribution of the comfort cooling components to the overall GWP for the assessed life cycle stages (A1-A3, A4-A5, B4, C1-C4) - calculated with EPD data

Component	**Amount**	**Unit**	**GWP** $(kgCO_2eq/m^2)$
Pipe and fittings	13350	kg	12,620
Valves	418	p	0,508
Circulation Pump	7	p	0,128
Cooling coils	86	p	6,220
Filters	1	p	0,001
Air separators	1	p	0,007
Expansion system	1	p	0,046
Insulation	546	m^2	0,613
Total			20,145

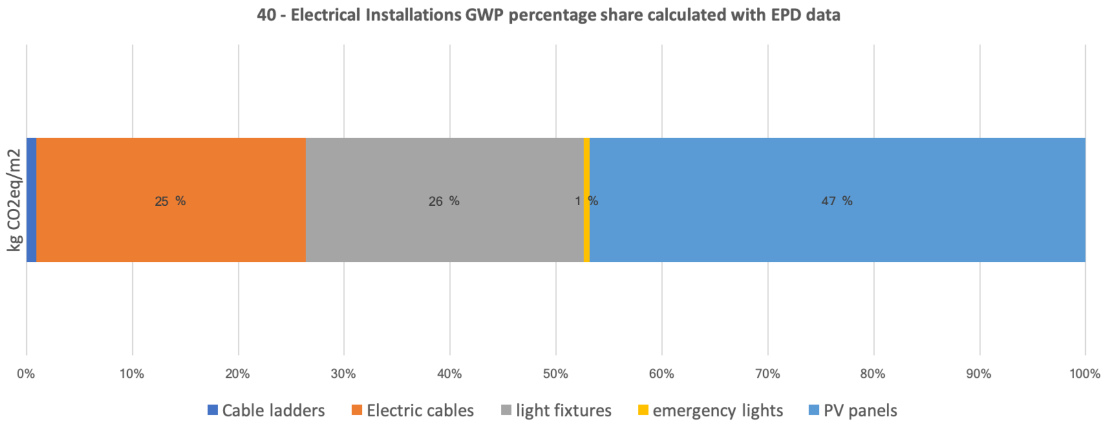

Figure 26: GWP percentage share of the included electrical installations for the assessed lifecycle stages (A1-A3, A5-A4, B4, C1-C4)- calculated with generic data

Table 18: Contribution of the electrical installation components to the overall GWP for the assessed life cycle stages (A1-A3, A4-A5, B4, C1-C4) - calculated with generic data

Component	**Amount**	**Unit**	**GWP** ($kgCO_2eq/m^2$)
Cable ladders	216	kg	0,366
Electric cables	20692	kg	10,226
light fixtures	2066	p	10,547
emergency lights	287	p	0,218
PV panels	500	m^2	18,831
Total			40,189

Description of digital Appendix

Digital Appendix A - BIM Files

Digital Appendix B - Datasheets and EPDs for components

Digital Appendix C - Inventory Data and Material Quantities

Digital Appendix D - LCA Excel results

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