Environmental-Friendly Ventilations

A Life Cycle Assessment of VAV and Active chilled beams system

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Master thesis in Energy-efficient and Environmental Buildings
Faculty of Engineering | Lund University

Lund University

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

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

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Keywords: Global warming potential fossil, Variable air volume, Active chilled beam, Life cycle assessment, Ventilation system

Publication year: 2024

Abstract

Based on the European commission, climate change has become a serious threat for all aspects of our lives, urgent action needs to be taken. All the industries need to monitor their contributions, among them the building industry has the highest emission (European Commission)
This study aims to compare energy efficiency and global warming potential (GWP_{fossil}) emission in two ventilation systems including Variable air volume (VAV) and active chilled beams (ACB) in their entire life cycles. The system boundary of this study covers Construction (A), use (B) and end of life (C) stages, however for use stage, maintenance (B2), replacement (B4) and operational energy use(B6) are calculated. The reference study lifetime of the project is 25 years.

Although A stage of two systems was calculated through a reference project, in this study thanks to newly published EPD the A stage is updated, and an uncertainty of data is calculated to assess the validity of A1-A5 results compared to reference study. An er simulation is done by IDA-ICE version 4.8 for B6 module calculation. This energy simulation only foc n energy use of fan, cooling, and heating of building. Finally, three scenarios are assessed for B6 module's results, including fossil-free energy target, and different geographical locations. Moreover, in order to assess the certainty of this module's results, two types of databases for B6 were compared including, average values provided by Boverket and location specific values provider by district heating network and electricity grid providers. For maintenance (B2), cleaning of HVAC systems is taken into account and for B4, the replacement of those products that have a lower service life span than 25 years are calculated.

Results indicate that ACB is more energy efficient than VAV, while the ACB system consumes more energy for cooling, it ultimately proves to be more energy efficient. Regarding GWP_{fossil} emissions, ACB in an entire life cycle perspective has a lower contribution compared to VAV. In both systems, B stage contributes to a higher share compared to A stage and C stage, due to the combination of operational GWP_{fossil} from B6 and GWP_{fossil} from replacement and maintenance.

Considering the impact of geographical scenarios on energy consumption and GWP_{fossil} emissions, ACB system consistently shows lower impacts across different locations. Additionally, the transition to future fossil-free energy sources significantly reduces operational GWP fossil emissions for both systems, highlighting the importance of focusing on the manufacturing process to lower embodied emissions. In summary, ACB shows superiority over VAV based on the gained results in this study.

Finally, by changing the fan operation schedules the results can be completely different compared to base scenario. Which means that the final decision will be affected by several aspects that needed to be taken into account.

Acknowledgments

Firstly, I would like to express my gratitude to my supervisor, Karin Farsäter, who guided me with her valuable knowledge and insights throughout this study. With her help, I have learned a great deal through this project. I also want to thank my co-supervisor, Christian Mattsson, who always dedicated his time and knowledge available to me.

In Lindab, I am thankful to Matilda Isaksson for providing this opportunity for me to deepen my practical knowledge in life cycle assessment science and ventilation industry through this study. I also extend special thanks to Kerstin Bergström for her guidance, expertise, and time in assisting me on this journey. Additionally, I would like to thank Ola Berg for dedicating his time to giving me Lindab's factory tour and providing information and insights into the ventilation production process. Moreover, I am thankful to Lars-Åke Mattsson who help me with his knowledge to make some wise assumption in my thesis.

In Assemblin, I would like to thank Daniel Barnekow, for his help and providing me with the necessary information to move this thesis forward, his constant help me to have a deeper insight into the project. I am also thankful to Fredrik Engdahl that with his thoughts and insights help me to progress this project.

In Swegon, I would like to thank Michael Börjesson, Carl-Ola Danielsson, Valon Emini, Elham Tamadoniyazdian, and Mikael Algotsson for their collaboration in promptly providing the necessary data for the project.

Lastly, I want to dedicate my sincere gratitude to my dear husband, Saeed Heidarian Dolatabadi, whose consistent support and continuous encouragement, were vital in helping me overcome the challenges of this journey to achieve my goals. This achievement would have been impossible without his presence.

Contents

List of Abbreviations

ACB	Active Chilled Beams
AHU	Air handling unit
BBR	Boverket´s building regulations
BOM	Bill of materials
CAV	Constant air volume
EPD	Environmental product declaration
EU	European Union
FTX	Fan ventilation with heat recovery & controlled exhaust and supply fan
GWP_{fossil}	Global warming potential fossil
HVAC	Heating, ventilation, air conditioning
LCA	Life cycle assessment
LCI	Life cycle inventory
OVK	Mandatory ventilation control
RSL	Reference service life
UAD	Underfloor air distribution
VAV	Variable air volume

1 Introduction

1.1 Background

Currently, climate change and global warming are considered as issues all around the world (European Commission). To address the climate crisis, the EU parliament has set specific targets, to make Europe the first climate-neutral continent on the globe by 2050. All the 27 EU members states have committed to fulfilling this goal in all the economic sectors (EU commission). To do so, many national regulations are adopted to achieve these targets in different sectors, and many tools and methods are introduced as a solution, like life cycle assessment as a tool to calculate the entire life cycle impact from products and services.

Among all the sectors, building sector contribute to the highest impacts, which means in Europe buildings have 40 % energy use, and 36 % of direct and indirect Green House Gases emissions from energy-related (EU Parliament, 2021). In Sweden, the construction sector's domestic emissions of greenhouse gases amount to approximately 12 million tons of CO_2 equivalents and shows about one fifth of the Swedish climate impact (Boverket, 2019). The highest emission from buildings comes from material use in construction and from operational energy use (Erlandsson et al., 2018). Currently, the climate declaration of Sweden does not include all the building components, like installations, but it has proposed to also include other building elements, like building services, for the next regulatory step of climate declaration by 2025 and adding the other life cycle stages in the climate declaration of buildings by 2027, because currently it only covers production and construction of products through their life cycles. (Boverket, 2019).

In recent decades, the usage of HVAC systems has increased in the office buildings, with aim for meeting the requirements of national building regulations to have a better indoor air quality, beside this, it is important to mention that the energy consumed by HVAC systems is almost half of the total energy consumption in building. (Chen, 2011; Hassan, 2019).

Reducing energy use through HVAC systems can be achieved by a life cycle approach in environmental aspects. Environmental aspects of HVAC systems are evaluated only emphasis on the initial stage of life cycle (A1-A3) of HVAC systems. Since the awareness of the importance of energy reduction in the whole life cycle is increasing among manufacturers and customers, both prefer to buy and sell more energy efficient systems in the long run. Considering both an entire Life cycle cost and life cycle assessment in HVAC industry can help to make the best decision both in design and systems selection (Johansson, 2005).

Currently, many studies focused only on construction (module A1-A3) and operational energy (B6) and showed that the highest amount of emissions come from these stages in the buildings (Boverket, 2019). It is worth noting that operational emission comes from non-renewable energy sources, such as fossil fuels. But in Sweden, district heating and electricity, are based on renewable energy sources, and it is also aimed to make them fossil-free by 2050 (fossilfritt sverige, 2018), which will result in significantly low emissions in B6 module. As can be seen in Figure 1, the operational emissions will decrease due to the carbon free grid, but embodied carbon from replacement and maintenance stage keeps staying high compared to operational emission. It emphasizes that to achieve carbon neutral target by 2050, an entire life cycle assessment of the built environment should be conducted, instead of focusing on some of the life cycle stages. (UNEP, 2023)

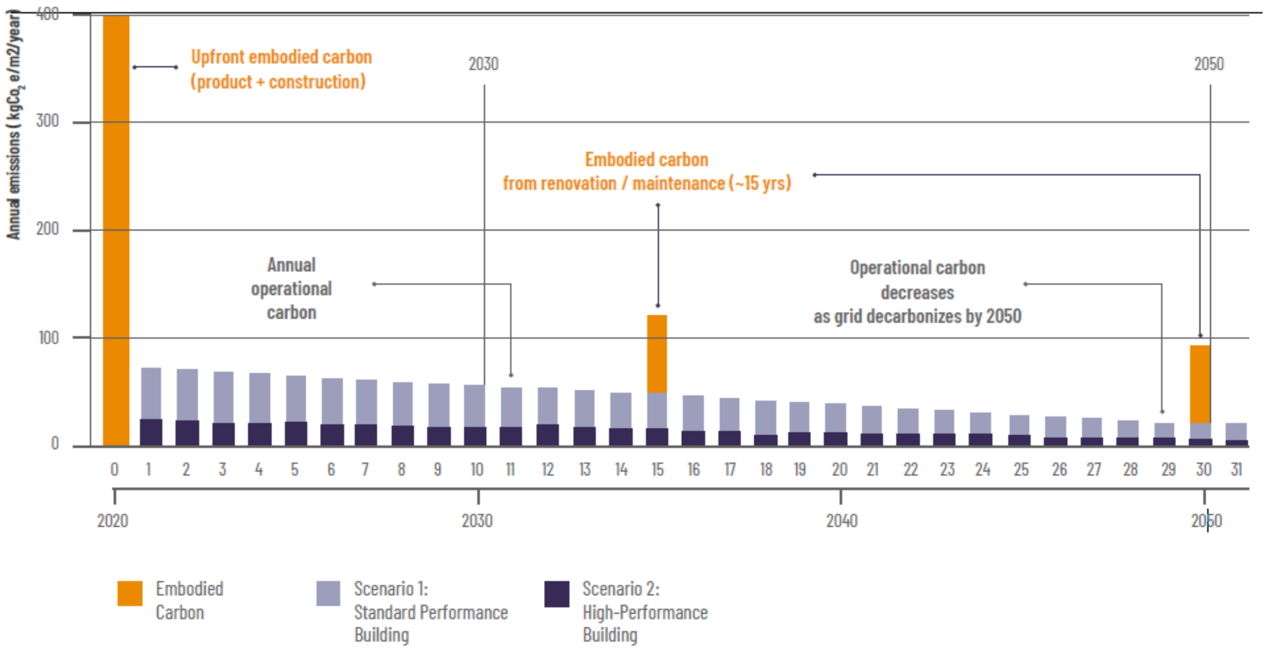

Figure 1: Embodied and operational carbon emissions over the building lifespan, Source: (UNEP, 2023)

1.2 Aim

In this study, by defining a case building project, supplied Assemblin, the entire life cycle assessment in Global warming potential $_{fossil}$ indicator of two different HVAC systems, including Active chilled beam and Variable air volume is evaluated and compared, and finally three sensitivity analysis was done for operational energy use module (B6), by considering different Swedish geographical locations and also future energy target.

1.3 Research Questions

The overall goal of this study is to calculate the entire life cycle assessment of two different HVAC systems, included variable air volume systems and active chilled beams systems, to compare their GWP $_{fossil}$ in an entire life cycle perspective and a sensitivity analysis is done to evaluate the impact of geographical locations and future energy target. The study will address the following questions:

1) Which system is more energy efficient in terms of total energy use consumed by fan, heating up and cooling down the case study building?
2) Which system represents the lowest total GWP $_{fossil}$, considering the entire life cycle?
3) Which system represents the lowest operational GWP $_{fossil}$ in the future energy scenario?
4) Which system shows the lowest operational GWP $_{fossil}$ results across different locations in Sweden?
5) Which system shows the lowest GWP fossil results in different fan operational schedules?

1.4 Research Objectives

This study aims to clarify that to select ventilation systems with lowest GWP $_{fossil}$ indicator, considering the entire life cycle assessment is a must. These parameters will be examined through various scenarios of the geographical locations and future energy to determine which system should be chosen as the most sustainable. The expected results should assess if the following statements are true:

1) The most energy-efficient ventilation system is also the system with the lowest GWP $_{fossil}$.
2) The ventilation system with the lowest GWP $_{fossil}$ may not have the lowest GWP $_{fossil}$ in the future energy target.
3) System performance in different locations differs; therefore, considering the building's location is crucial when selecting the systems.

4) System performance in future fossil free energy differs; therefore, considering future estimation is crucial when selecting the systems.
5) System performance in different fan operational schedules differs, therefore, considering the importance of fan operation is crucial when selecting systems.

1.5 Limitations

- The analyses solely focus on the VAV and ACB systems, excluding other installations.
- This study only concentrates on global warming potential $_{fossil}$, based on calculation method in SS-EN 15804 standard.
- An entire life cycle assessment (Cradle to grave) is calculated throughout this study.
- Due to the complexity of gathering data B1, B3, B5 modules are excluded in this calculation, and only B2, B4, and B6 are calculated for the used stage.
- This study has focused on the HVAC systems themselves in LCA, not a comparison between products from involved manufacturers.
- This study does not focus on the design of VAV and ACB systems, these systems were designed prior to this thesis.

1.6 Structure of report

Chapter 1 introduces background, research questions, research objectives and limitations. *Chapter 2* discusses theory related subjects. *Chapter 3* explains literature review and related studies that has been done on this subject. *Chapter 4* elaborates the methodology that is used in this study for energy simulation and LCA calculation. *Chapter 5* presents obtained results. *Chapter6* discusses the results. *Chapter 7* summarizes and concludes the study and *Chapter8* gives recommendations for future works.

2 Theory

2.1 HVAC System Descriptions

In this study the two HVAC systems are studied, including Variable volume air system (VAV) and Active chilled beam (ACB). In the following part the description of each system is provided.

2.1.1 Variable volume air system (VAV)

The VAV system is a ventilation system that provides conditioned air with air handling unit through fan and ducts (Fellegvari, 2023). Airflow in this system varies during the operational time with the help of a controller that regulated room temperature and its air quality.
Terminal units in VAV system, called VAV box, are in each zone and control variable airflow with a constant temperature and velocity(Fellegvari, 2023). A VAV box controls variable airflow by being closed and opened according to the room's cooling demand. Based on the changes in airflow, the main fan of the system will slow down or speed up (Chen, 2011). See Figure 2.

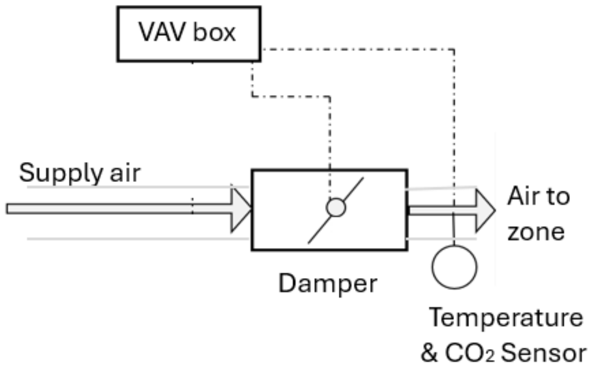

Figure 2: VAV terminal control box with integrated reheat principle, Source: (Fellegvari, 2023)

2.1.2 Active chilled beam (ACB)

Active chilled beam (ACB) is an air-water convection units that is integrated with a central constant air volume (CAV) air handling unit (Fellegvari, 2023). It provides cooling through chilled water pipes and maintains the air quality with fresh air. This primary fresh air also can help to reduce the temperature of the return air. The function of this system is to rely on convection between chilled pipes and the room's air (Chen, 2011).

The ACB systems principles are worked by a guided airflow through a series of nozzles, where it is expelled at high speed into a mixing chamber, generating a low-pressure area above the cooling coil. This pressure contrast makes room air move upward through the coil. Subsequently, this induced air passes through the coil for cooling purposes. After cooling, the induced air is blended with the primary airflow and then diffused back into the room, see Figure 3 (Fellegvari, 2023).

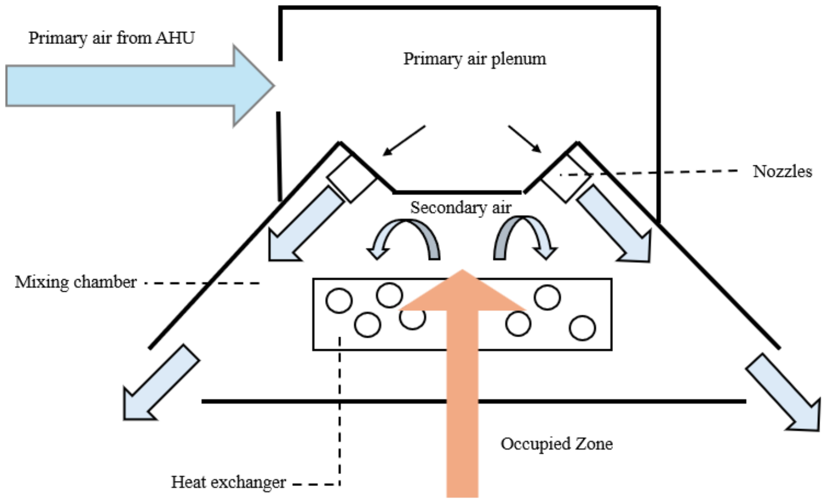

Figure 3:ACB principle, Source: (Fellegvari, 2023)

2.1.3 ACB and VAV System comparison

Both VAV and ACB systems are designed to meet the cooling demands of the buildings, the cooling demand shows the difference between internal heat gains and heat losses (Fellegvari, 2023). The main difference between these two systems is their thermal medium. In VAV, air is the only thermal medium that provides cooled fresh air, while in ACB, there are two thermal mediums, water, and air, and this can separate the ventilation load and rooms' load (Fellegvari, 2023). Decoupling these two loads resulted in a lower need for air flow rates (Fellegvari, 2023). Considering this lower airflow rate, a 17% reduction in fan energy use is reported in ACB compared to VAV (Alexander; et al, 2008; Fellegvari, 2023). In addition, because the airflow in ACB is lower than VAV, accordingly AHU and ductworks sizes are less than VAV (Fellegvari, 2023).

2.2 Life cycle assessment and climate calculation

Life cycle assessment is a standardized and science-based method to collect and evaluate the potential environmental impacts of products and services throughout their entire life cycles (One click LCA). These potential environmental impacts include climate impact or Global Warming Potential (GWP), acidification, eutrophication, acidification and more (Boverket, 2019). The focus of this thesis project is only on climate impact or GWP $_{fossil}$ indicator.

Each LCA divides into three different mandatory stages, including construction stage (A), use stage (B), and end of life stage (C), and an optional stage called reuse or recycling potential (D) (EN15978, 2011). These stages have their own different modules as can be seen in the following Table 1. Doing an LCA covering stage A to stage C, it is called cradle to grave, which is the focus of this study. To achieve the target of being carbon neutral, a comprehensive understanding of life cycle assessment can be crucial(One click LCA).

Table 1: Stages and processes included in the climate declaration act.

Stage		Module	
		Prefix	**Processes**
Construction stage	Production stage	A1	Raw material supply
		A2	Transport
		A3	Manufacturing
	Construction process stage	A4	Transport
		A5	Construction/installation onsite processes
Use stage		B1	Use
		B2	Maintenance
		B3	Repair
		B4	Replacement

	B5	Refurbishment
	B6	Operation energy use
	B7	Operation water use
End-Of-Life stage	C1	Deconstruction
	C2	Transport
	C3	Recycling/Reuse
	C4	Disposal
Benefit and loads outside the system limits	D	

In an international scope, ISO, the International Organization for Standardization, issues the standard and technical aspects of LCA throughout a series of standards. The representative of ISO in Sweden is SIS, Swedish institution of standard (Boverket, 2019b). There are many standards that cover different industries, but based on Boverket, environmental declaration related to construction industry is provided by the following standard in Table 2:

Table 2: Environmental calculation standards

ISO 14020	Different types of environmental impact reporting
ISO 14025	Environmental Product Declarations (EPDs)
ISO 14044	Life Cycle Assessment (LCA) methodology
SS-EN 15804	Core regulations for the product category of construction products
SS-EN 15978	Calculation method for sustainability of construction works

2.2.1 System boundaries

In this section the systems boundaries covered by this study are explained, including construction, use stage and end of life stages.

Production Stage (A1-A3)

This stage includes A1, material extraction and processing, A2, transport to the manufacturer, A3, Manufacturing process (EN15978, 2011).

Construction Stage (A4-A5)

Regarding A4, which is transportation from factory to construction site, it is related to the amount of GWP_{fossil} emitted during this transportation. Module A5 stands for installation of products in construction site, Based on EN15978, this module also includes the waste during installation, in EPDs it can be found that this waste is only from packaging or material waste (EN15978, 2011).

Use Stage (B2, B4, B6)

The use stage covers the impacts from products' usage during their usage time, this usage time can be varied for each product (Boverket, 2019; EN15978, 2011). Based on the EN15978, in B stage only those modules with higher share in climate impact must be taken into consideration, including Maintenance (B2), replacement (B4), operational energy use (B6) (Boverket, 2019; EN15978, 2011).

B2- Maintenance

This module includes combinations of all the planned and scheduled inspections to keep the performance of the product as it is intended. It also includes cleaning and the energy used for cleaning purposes (Boverket, 2019). According to the SS-EN 15978, B2 includes the processes that makes a product to be maintained in its intended performance (EN15978, 2011). In addition, Boverket, recommended to also consider periodic maintenance inspections for the calculations under B2 module (Boverket, 2019). The boundary of B2 includes:

- The production and transportation of any products necessary for used during maintenance.

- Transportation of any waste produced during maintenance or transportation related to maintenance.
- The end-of-life process of any waste during transportation and maintenance (*EN 15804*, 2019).

B4- Replacement

Replacement includes replacing a broken component or a part of that due to its end of life. The boundary of this module includes:

- The production and transportation of new product that is going to be replaced.
- The end-of-life process of the removed product (*EN 15804*, 2019).

There is a lack of clarity in EU standard to distinguish B2 from B4, therefore in LCA studies it permits to have different interpretations and method across different countries (Boverket, 2019).

B6- Operational Energy Use

This module covers the energy operation of a products during their operational time. For this module, it is important to define the energy carrier as mentioned in Boverket (Boverket, 2019). The energy carriers of this study include district heating for heating and electricity for cooling and fan energy use.

End of Life Stage

This stage includes the waste processing of products when they no longer last (Boverket, 2019b). The aspects that modules in C stage cover are explained as follows:

- C1: if a device or machinery is used f for demolition a component the imoact for the energy used of this process is consider under this module (Boverket, 2019b). If a component can be demolished manually this module will be zero.
- C2: the impact from energy used fo transportation of demolished component to the waste locations is consider in this module (Boverket, 2019b).
- C3: the waste treatment procedure impacts, including reuse, recycling, and energy recovery of demolished component is calculated under this module (EN15978, 2011).
- C4: this module covers any process including incineration, landfilling, etc. which are necessary before final disposal (EN15978, 2011).

2.2.2 Swedish Building Climate Declaration

Sweden is one of the countries that set mandatory climate declaration for new building built after 2022 (Boverket, 2019b; Olsson Annika & Lindab AB, 2002). The aim of this declaration is to increase the awareness of construction developer on the climate impact of building's products (von Malmborg et al., 2023). In 2022, the first climate declaration of building was provided by National Board of Housing, Building and Planning, Boverket, as a method for upcoming regulations. The methodological basis of this legislation is based on EN15978 standard, which stands for Swedish standard addressing construction products. Another proposal is published which will be set by 2025 and 2027, the aim is to make it more broaden and comprehensive by adding more building components and LCA stages. The differences between the current and new proposal legislations are shown in Table 3 & 4. Table 3 shows the new proposed modules to be included in the climate declaration calculations compared to current one.

Table 3:Different LCA stages covered in different Climate Declaration Proposal

Life cycle stage	A1-A5	B1	B2	B3	B4	B5	B6	C1	C2	C3	C4	D
2022	×											
2027	×		×		×		×	×	×	×	×	

Table 4 shows the current building components considered in climate declaration compared to new proposal.

Table 4:Different building component considered in different Climate Declaration Proposal

Building component	Load-Bearing Structure	Building envelope	Interior walls	Installations	Interior surface finishes	Room fitting
2022	×	×	×			
2025	×	×	×	×	×	×

2.2.3 Framework

Each life cycle assessment follows a repetitious framework based on the ISO 14040, which consists of four stages. Each LCA primarily starts with defining goal and scope that includes systems boundary and functional unit, followed by Inventory analysis that is called life cycle inventory (LCI), which includes product's inputs and outputs related to the system boundaries. The third phase is impact assessment, there are many different environmental impacts that are followed by defined LCI in previous phase. And finally, interpretation of results aims to explain the results based on the scope and goal of the assessment.(Hassan, 2019). See Figure 4.

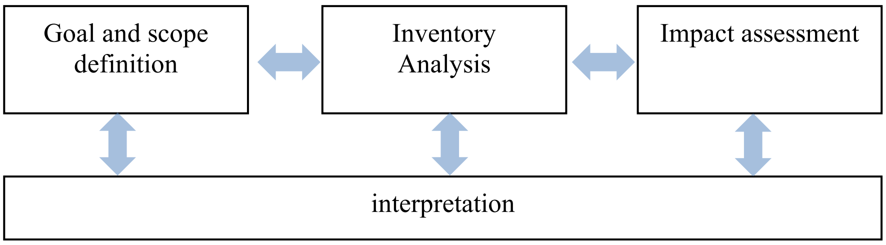

Figure 4: framework of LCA calculation.

2.2.4 Data inventory

There are two types of climate data for LCA calculation including generic data and product specific data. Generic data is a generic indicator for environmental impact of a group of material or products based on an average value. While Product specific data is also called Environmental Product Declaration, EPD, calculated based on SS-EN 15804 +A2, for a specific group or individual of products. Using either generic data or EPD depend on the aim of the LCA calculation and the availability of EPDs (Boverket, 2019b).

Generic data for installations

Generic climate data refers to average values for construction products in the Swedish market, calculated based on previous life cycle analyses, this data is accessible for public (Boverket, 2023). There are several sources that provide generic database including, available for the Swedish construction industry include the Swedish National Board of Housing's climate database, the Swedish Transport Administration's Climate Calculator, and the Finnish climate database (CO2data.fi). Boverket climate data covers A1-A5 while Finnish generic database covers only A1-A3 (Abuayyash, 2024).

Product- Specific data, EPD for installations

Environmental product declarations are provided by manufacturers for specific products and needed to be reviewed by a third party. For approval a registration on EPD program is required, including The International EPD System, The Norwegian EPD Foundation (epd-norge.no), or EPD Hub. This database is valid for three or five years. Each EPD calculation based the product category needs to follow PCR. A PCR is a guide for calculations. Based on the Bovereket LCA+PCR= EPD (Abuayyash, 2024; Boverket, 2019a).

2.3 Swedish Electricity and District Heating Mix

Sweden has 4 different electricity zones, and each zone has its own combination of sources and specific amount of CO_2 emission (electricitymaps, 2024). Meanwhile, for district heating even in one county there are many different providers with different CO_2 emissions (energiforetagen.se, 2023).The energy delivered to the customers is the measure calculated carbon dioxide equivalents by different providers (energiforetagen.se, 2023).Therefore, each electricity zone and district heating provider has a specific GWP_{fossil} emission, these values are considered location specific values that need to be used for emission from B6 module.
Boverket with an aim of simplicity in calculation, has provided an annual average of GWP fossil emission from electricity carriers, 0,037 (kg*CO_2e/kWh) and district heating 0,056 (kg*CO_2e/kWh) for the whole country (Boverket, 2019b), and suggested to use these average values for B6 calculation.

3 Literature review

A thesis with the title of Analysis of climate impact from ventilation systems in terms of design and system selection in office buildings (Swedish:Analys av klimatpåverkan från ventilationssystem vad avsernutformning och systemval I kontorsbyggnad)was conducted by Sarah (Ola) Abuayyash and Ada Kajtaz in collaboration with Assemblin. The focus of this study is to investigate the climate impact of the Variable Air Volume (VAV) system in the Priorn office building in Malmö. The global warming potential of different components of this ventilation systems were analyzed to determine which one has the highest impact and how their impacts can be reduced. In this study, the climate calculations focus only on A1-A3 (product module) and A4-A5 (construction production module). Finally, three improvements were analyzed including replacing traditional ducts with insulated ducts, replacing VAV system with ACB system, replacing traditional ducts with recycled steel ducts. The best improvement was using insulated ducts and recycled steel ducts (Abuayyash.S , et.el, 2023).

An article conducted by Ylmén et al. (2019) with a title of Life Cycle Assessment of an Office Building Based on Site-Specific Data, the goal of this study was to examine the critical part of the construction in terms of environmental impacts. The system boundary of the study covers A1-A5, B4, B6, C1-C4. Global warming potential (GWP), eutrophication potential (EP), acidification potential (AP), stratospheric ozone depletion potential (ODP) and photochemical oxidants creation potential (POCP) according to EN 15804 were calculated. Results show a considerable contribution from the HVAC-system, it can be because of the dominant material which is steel and replacement of several components due to their end of lifetime.(Ylmén et al., 2019)

There has also been a thesis carried out with Lindab with a title of life cycle assessment of two ventilation systems with a goal of comparing LCA of two different types of ducts in HVAC system. The LCA stages that were taken into consideration were A1-A5 and B6. The results showed that the difference between these rectangular and circular ducts is not significant, but by focusing on the B6 stage, it was understandable that heater and fan energy consumption has the highest contribution to the studied environmental impact. That emphasized the importance of considering operational energy in calculating LCA of HVAC systems (Annika Olsson, 2002) .

Another thesis was done by Nadeen Hassan in collaboration with Lindab with a title of Life cycle assessment of a CAV, a VAV, and an ACB system in a modern Swedish office building on three types of HVAC systems including CAV, VAV and ACB for a modern office building in Sweden. LCA was done for cradle-to-gate and operational energy of each system. Finally, by using different materials and energy mix, three scenarios were analysed. The results showed that ACB has highest environmental impact during manufacturing stage, while CAV and VAV have higher environmental impacts in operational phase, respectively. Moreover, comparing different energy mix showed that 100% renewable energy can reduce both high environmental impacts of manufacturing of ACB and operational energy of CAV and VAV (Hassan, 2019).

A thesis was conducted by Shuo Chen with a title of system dynamics-based models for selecting HVAC systems for office buildings: a life cycle assessment from carbon emission perspective, focused on evaluating the environmental impact of life cycle terms of HVAC systems. The results showed that, for VAV and underfloor air distribution (UAD) operational has higher contribution, while in ACB manufacture and maintenance have higher portion compared to operational stage (Chen, 2011).

A paper was written by Yah Y.H. and Tam J.H. with a title of a comparison study for active chilled beam and variable air volume systems for an office building, to compare ACB and VAV systems in terms of cost and energy efficiency. The results showed that even though ACB has higher initial cost, it gives a better saving in running cost related to energy (Yau & Tam, 2018).

Previous studies in the field of environmental aspect by HVAC systems, have researched in different aspects such as impact of material, design, and energy use. Manufacturing and operational use are mentioned as an important aspect that needed to be focused on to reduce environmental impact from HVAC systems.

4 Methodology

In Spring 2024, Lindab and Swegon intended to conduct a study to compare the entire life cycle assessment of two types of HVAC systems, including VAV and ACB. In order to establish a well-defined project boundary, Lindab and Swegon, in consultation with Assemblin, proposed to continue a previous study done by Sara and Ada (Abuayyash, 2024) as the reference for the current study. In this report, the previous study is referred to as the reference study. This chapter introduces the reference study and methodology applied for energy simulation, LCA, and sensitivity analysis of B6.
It is worth mentioning that for some parts of this report, with the aim of improving writing language AI, such as ChatGPT, is used. Moreover, the graphs and figures used from reference study, are made, and modified again by the author of this current study by having approval from reference study's writers.

4.1 Case Study Building

The case study building of this project is Priorn located in Malmö, see Figure 5, with 4 different building blocks, one block has eight floors, and the others have five floors. It has 18 500 m^2 total gross floor area. It includes offices, stores, and clinic spaces, see the different room types in Table 5. The building owner is Vasakronan, it was designed by White Arkitekter and constructed by MVB company. This building has been awarded the Green Ribbon Environmental Building Prize in 2021. It is well-known because of its geothermal energy system, which supplies the Priorn and neighborhood buildings. This building has been certified with LEED Platinum (Abuayyash & Kajtaz, 2023).

Figure 5: Priorn Building (White arkitektur, 2020)

Table 5: Room type in each floor in Priorn building (Source: Abuayyash, S; Et. el, 2023)

Floor	Room Type
1	Garage, geothermal energy, changing rooms, fan room, electrical and telecommunications central, storage
2	Shops, offices with changing rooms, environmental room, sprinkler central, and courtyard
3	Offices, memory clinic with biobank
4, 6, 7, 8	Offices
5	Offices, memory clinic with changing rooms, gym, and rooftop terrace
9	Rooftop level with technical room

4.1.1 Existing building heating and cooling systems

The existing ventilation system in Priorn building is VAV system. Based on the Assemblin technical document, there are 4 AHUs equally sized on the basement floor, all of them have a 7210 l/s design airflow. The supply air grills are located on the 9th floor. There is also one AHU with only supply air fan that supplies the supply air for the garage. The exhaust air hood is in the courtyard. The units include filters, rotating heat exchangers, shut-off dampers, post-heating coils, and cooling coils (Abuayyash & Kajtaz, 2023). All the products and components that are installed in this VAV system are listed in a bill of materials file (BOM), their quantity, types and manufacturer are defined there.

4.2 Description of the Reference Study

In 2023, a study was done in collaboration with Assemblin, to analyze the climate impact of ventilation system of Priorn building located in Malmö in order to reduce this impact from this ventilation system and identify the critical material in this system, being able to assess and introduce more sustainable alternatives (Abuayyash, 2024). This study focused only on climate impact (GWP $_{fossil}$) for A1-A5 of ventilation system. After calculating the climate impact of VAV system, three different improvements were assessed including:

1) Replacing traditional duct systems with insulated ducts called soft ducts.

   These types of ducts consist of insulation coated with foil; they are not common in Sweden. A manufacturer named Climate recovery is producing this type of circular ducts, bends, and T pieces. According to this manufacturer, there are two benefits for these ducts, lower pressure drops and less need to add sound attenuator. These types of ducts are transported in flat sheets, and this can make transportation easier. Another manufacturer that produces rectangular types of these insulated ducts is ISOVER, they are also cut, folded and taped on site (Abuayyash, 2024; Climate Recovery). See Figure 6.

Figure 6: Insulated ducts (Soft ducts); source: (Abuayyash, 2024; Climate Recovery)

2) Replacing the VAV system with ACB with a constant airflow.

In this improvement, by designing an ACB system, its climate impact was calculated in comparison with VAV system. This ACB system supplies the constant airflow of the minimum requirement of Swedish Work Environment Authority's guidelines for workplace ventilation, which is equal to 7 l/s per person plus 0.35 l/s per square meter. Designing this system was conducted by using the same room’s cooling power that was calculated for the VAV system. This cooling power is determined by the number of occupants, lighting and cooling internal loads and solar radiation. The number of chilled beams for each room was calculated and finally the vertical and horizontal pipes for chilled water were measured, quantity of insulation and control valves needed for this system were also determined. Ductwork and AHU sizes were adjusted based on the required airflow for this new system. And finally, the climate impact of the total system was calculated (Abuayyash, 2024).

3) Replacing the traditional ducts with recycled steel ducts.

In this improvement, the traditional ducts were replaced by recycled steel ducts which are produced by 100% renewable energy and have 70% lower climate impact. These recycled ducts are sourced by Lindab (Abuayyash, 2024).

The results of VAV system in comparison with three improvements are shown in Figure 7. Comparing these three improvements, the most effective improvements were insulated soft duct and recycled steel ducts, respectively. Although switching from VAV system to ACB is less effective than the other two alternatives.

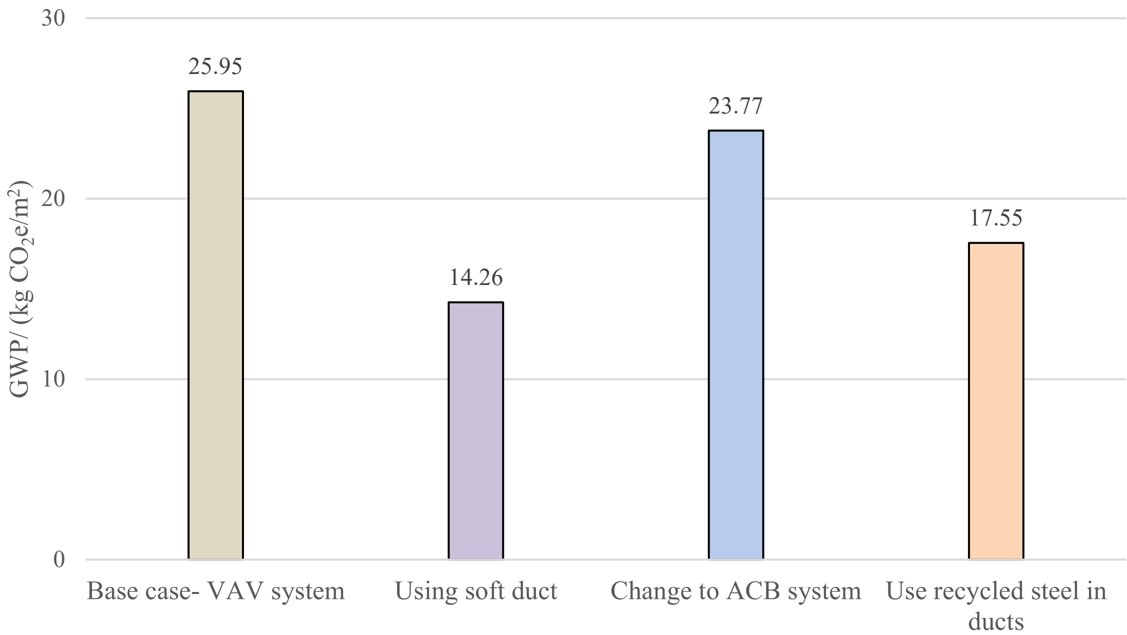

Figure 7: Climate impact of VAV compared to three improvements in reference study, source: (Abuayyash, et al, 2024)

In this current project, the aim is to compare GWP $_{fossil}$ emission through the entire life cycle of VAV system with ACB system, second improvement. The other improvements are not covered in this project. For reaching to this aim, three steps are taken in this current project, including:

1. In case of having any new published EPD, they are replaced with previous data used in reference study for A1-A5.
2. Energy use calculation of Priorn building is conducted by considering the installed VAV and ACB systems in this building and using the results for calculating GWP $_{fossil}$ for B6 module.
3. Calculating and comparing GWP $_{fossil}$ emitted by replacement and maintenance module for each system.
4. Calculating the end-of-life stage of each system.
5. Finally, comparing total GWP $_{fossil}$ from both systems.

All the calculations steps are explained in the following sections. Since this current study follows the reference study's method, in order to have understanding of the LCA method, the approach taken in reference study is also explained.

4.3 Energy use calculation

Building energy simulation was conducted through IDA indoor climate and energy (IDA-ICE) version 4.8. IDA-ICE is a simulation tool designed for in-depth, year-round analysis of thermal indoor conditions and the overall energy usage within a building (E.Q.U.A, 2024).
First, a building 3D model and input values were provided by Assemblin. Those rooms that have the same indoor climate were considered as the same group thermal zone, see Figure 8, categorized in office rooms, clinic rooms and shopping stores, see their input in Table 6-9. Moreover, energy simulation result validation is compared with a report of energy simulation done by the building's constructor, MVB company. Therefore, a

10% margin compared to the MVB's results was considered. The energy simulation in this project focuses only on fan energy use of HVAC system, energy for heating up, and cooling down the building. Moreover, each system energy simulation was redone, by changing the weather file in IDA ICE for 4 different locations in Sweden, the criteria for choosing these locations are explained under Section 4.2.3. For the energy simulation instead of considering 4 separate AHUs in IDAICE, one AHU with a total airflow of four units is considered.

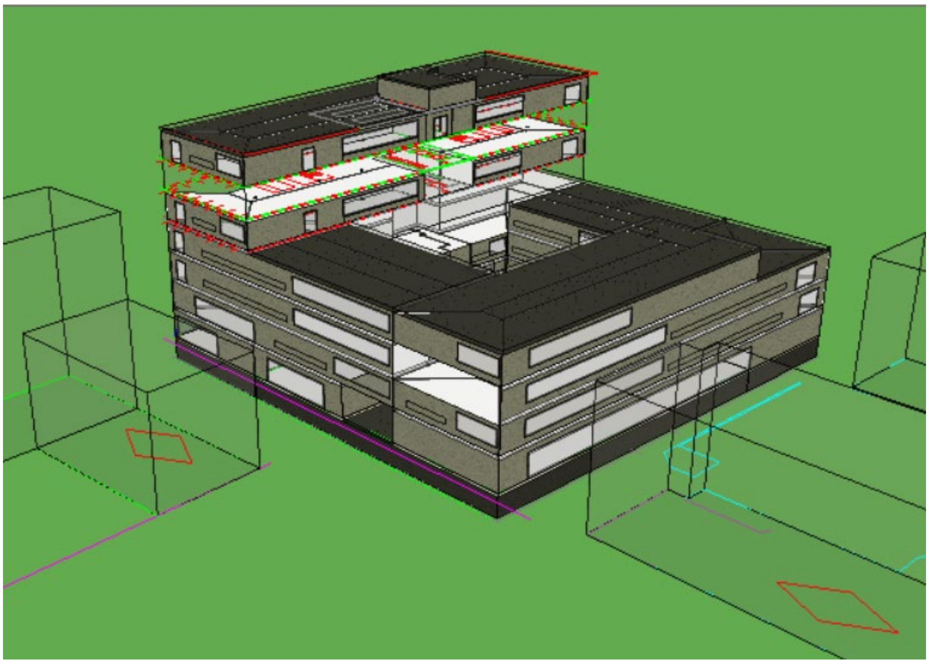

Figure 8: IDAICE model of building.

Table 6: Occupancy schedules in IDAICE, Source: (MVB, 2020)

Schedule type	Person densities/ (m^2/person)	Rate of attendance	Using time
Occupancy office rooms	20	70%	8-17 weekdays
Occupancy clinic rooms	20	60%	8-17 weekdays
Occupancy stores	3	30%	10-19 weekdays

Table 7: Equipment Schedules, Source: (MVB, 2020)

Type	Heat from equipment/ (W/m^2)	Rate of use	Using time
Equipment in office rooms	12.2	70%	8-17 Weekdays
Equipment in clinic rooms	9.3	60%	8-17 Weekdays

Table 8: Lighting Schedules, Source:(MVB, 2020)

Type	Heat from Lightings/ (W/m^2)	Rate of use	Using time
Lighting in office rooms	3 W/m2	70%	8-17 Weekdays
Lighting in clinic rooms	3 W/m2	60%	8-17 Weekdays
Lighting in stores	3 W/m2	100%	8-19 weekdays

Table 9: Temperature setpoint used in IDAICE, Source:(MVB, 2020)

Temperatures	Summer	winter
Supply air temperature set point	If ambient is between -15 to 40 °C supply air is 12 °C	If ambient is between -20 °C to 5 °C supply air is 15 °C
Office temperature set point	25 °C	20 °C
Stores temperature set point	25 °C	20 °C
Clinic temperature set point	25 °C	20 °C
Garage temperature set point	5 °C	18 °C

The energy carriers for heating, cooling and domestic hot water used for energy simulations are shown in Table 10.

Table 10: Energy parameter, Source:(MVB, 2020)

Energy Parameter	Energy carrier	COP/EER
Heating	District heating	2.5
Cooling	Electricity	3.5
Domestic Hot Water	District heating	1

4.3.1 VAV system

The total minimum designed airflow for this system is equal to 28 840 l/s, and the maximum airflow is 35 020 l/s In IDA-ICE, the system type in IDA-ICE is chosen VAV with temperature and CO_2 sensor, this sensor will regulate the supply air for each room, which means that in this system fan follows the rules from room unit sensors to change the airflow. See Table 11.

Table 11: Fan operational, Source:(MVB, 2020)

VAV Fan operational use	Always on, but minimum airflow during unoccupied hours

In the current study in consultation with Swegon, the AHU of VAV system was replaced with Gold RX 80/120 units of Swegon. The other ventilation products of VAV system are as there were in reference study.

4.3.2 ACB system

For ACB system, the AHUs with CAV principle were considered with total airflow of 22751 l/s. The difference between this system with VAV system in IDA ICE, is the schedule of fan, in ACB, fan operation schedule only works during occupied hours, while in VAV that the airflow regulates with CO_2 and temperature sensors, which means that fan is always on (Börje Lehrman, 2024). Table 12 shows the fan schedule of ACB system. The minimum ventilation rate as the hygienic airflow for each room was calculated based on the following equation (1) from BBR (Boverket, 2019):

$$q = 0.35\ l/(s.m^2 floor) + 7\ l/(s.occupant) \tag{1}$$

Table 12: fan operation schedule in ACB

ACB fan operational use	Only during day, off during night

It is worth mentioning that, in reference study, ACB system was not designed with detailed approach. Therefore, after consultation with Swegon experts, previous chilled beams from reference study were replaced with Swegon Parasol 1200. Moreover, the AHU of ACB system, in consultation with Swegon were replaced with their GOLD RX 50/60 AHUs.

4.4 Life cycle assessment implementation

This part describes the method applied for LCA calculation, due to the dependency of current project on the reference study, both methods are explained here.

4.4.1 Functional unit

In this study the aim is to compare GWP $_{fossil}$ emitted from entire life cycle of two HVAC systems installed in the same building, with the same designed condition. The functional unit of this study is one ventilation system with a 25 years' service time that ventilates one square meter of gross floor area (BTA) of Priorn building.

4.4.2 System boundaries

In this study, life cycle assessment is calculated based on the SS-EN 15978, covered stages in this project include: construction, use and end of life stage. The A stage was conducted through the reference study but also updated during current study. B stage, (B2, B4, B6), and C stage are calculated in this current study with an entire life cycle approach.

4.4.3 Method of calculation

In this project it is tried to follow the same method of calculation as reference study to obtain more reliable and uniform findings.

Reference study

In reference study by using bill of material list (BOM), a list of components with their quantities and measures, in excel was created for LCA calculation. The components in this excel were categorized based on their functions, these categories are shown in Table 13. Each category is divided into different products based on their size and types. See Appendix A, B and C, showing the excel sheet for VAV dampers AS an example.

Table 13: The Excel file category for LCA

Category
Diffuser
VAV-diffuser
Damper
Fire damper
Damper in VAV
Silencer
YG, Protective grill, Hood, Cleaning hatch
AHU
Circular duct products
Rectangular duct products
Insulation
Chilled beams

The overall method applied in reference study is shown in Figure 9. By multiplying the climate footprint of each product by its weight and summed them up, the total climate footprint was calculated (Abuayyash, 2024). Finally, the mentioned improvements were suggested.

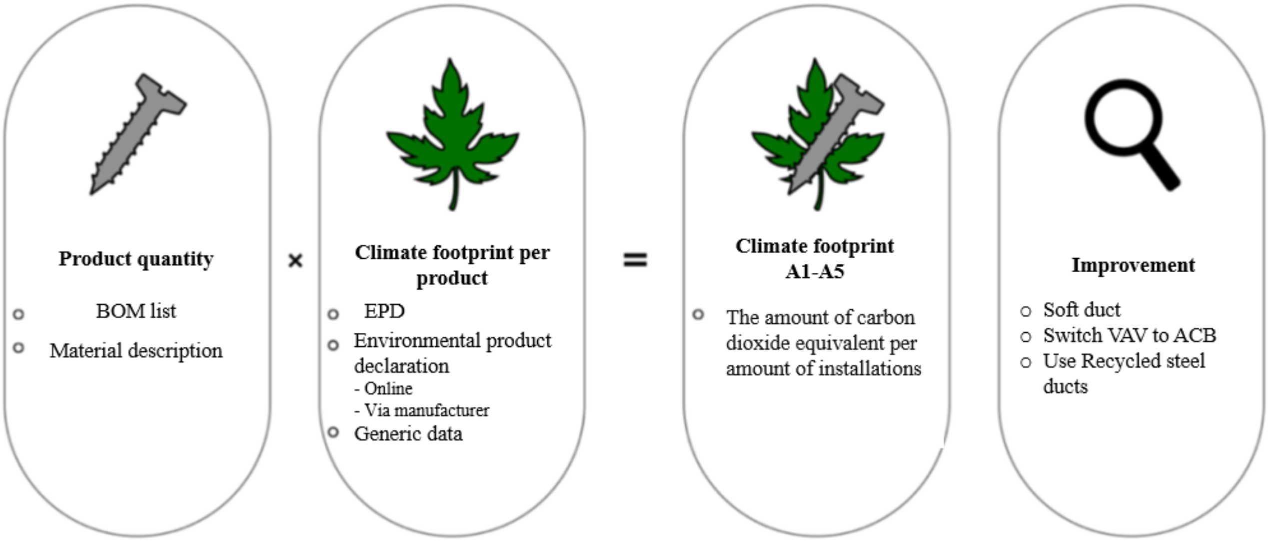

Figure 9: Reference study calculation method Source: (Abuayyash, 2024).

Production and construction stage

Regarding calculation of A1-A5 in reference study, there are some important aspects that worth mentioning here, for more information please refer to reference study's report. The climate calculation of VAV system was done based on the Boverket's calculation rules, the taken steps are as follows:

1- Calculating the products' weight under each category (Abuayyash, et al ;2024).
2- For each product, GWP $_{fossil}$ values were found from available data by using three principles, including:
   - In case of availability of EPD, they were used for calculation.
   - If there was no EPD, Finnish's generic database was used.
   - If there was no EPD and generic data for a product, based on the material description from manufacturers, the impact from materials were calculated, this assumption is called componentized (Abuayyash, et al ;2024).
3- Product's GWP $_{fossil}$ was calculated for each stage from A1 to A5 and then total value of this indicator was calculated for each product (Abuayyash, et al ;2024).
4- Three improvements were proposed based on the critical components results (Abuayyash; et al; 2023).

The final result from product's category in both VAV and ACB systems is shown in Figure 10.

It is worth mentioning, since Finnish generic data does not report A4; therefore; for those products that generic data was used, A4 value was taken from another reference study by LFM30 (Abuayyash, 2024). Regarding A5, for those ventilation's components that are sent as an individual piece in construction site, no waste is produced from material content, only packaging waste that according to SS-EN 15978, this waste should not be included in climate calculations. Therefore, A5 module was excluded for individual pieces of component like dampers, silencers, fans, and diffusers, as well as rectangular ducts that are cut by the manufacturer, but for components like insulation and circular ducts that are cut in the construction site and generate material waste, A5 is considered (Abuayyash Ada Kajtaz, 2023).

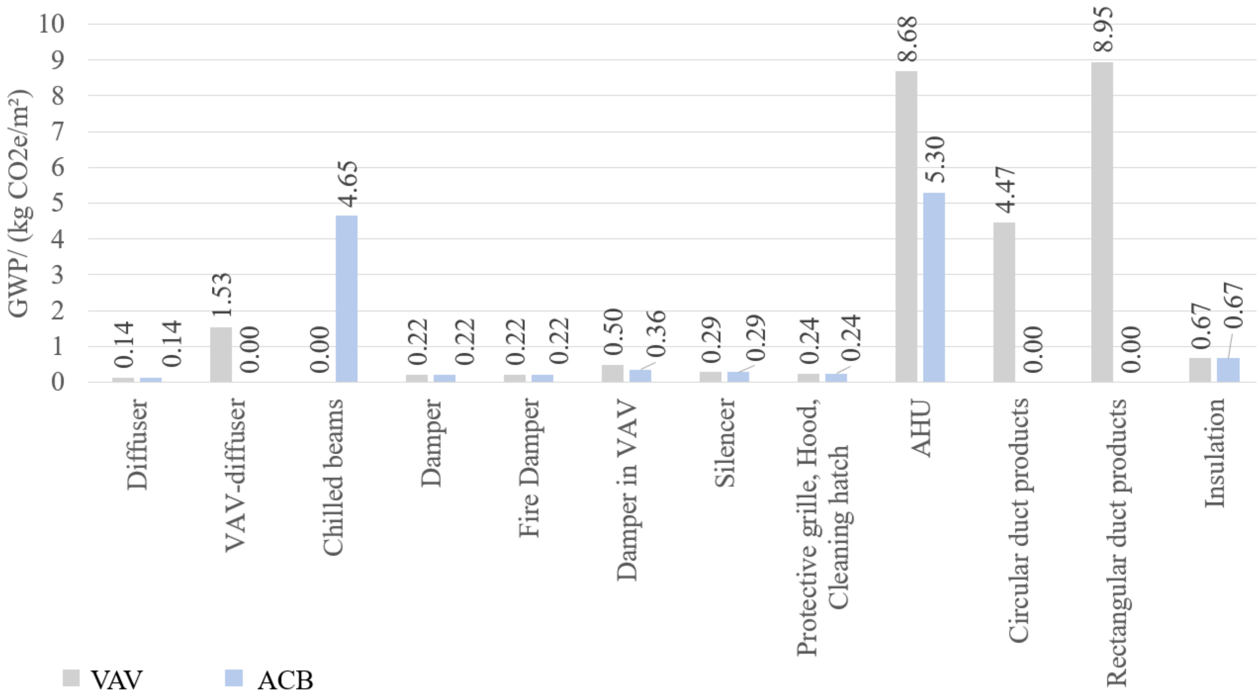

Figure 10: Reference study's result for GWP_{fossil} in ventilation's components in VAV and ACB system. Source: (Abuayyash, 2024)

Current project

The overall process of current project calculation is shown in Figure 11. As mentioned earlier, first, an energy simulation is done in IDAICE to calculate the total energy use in Priorn building. By using the energy simulation results B6 module is calculated. Finally, a sensitivity analysis is done for different weather in Sweden and future climate target. B2, B4 and C stage also are calculated with the same method as reference study.

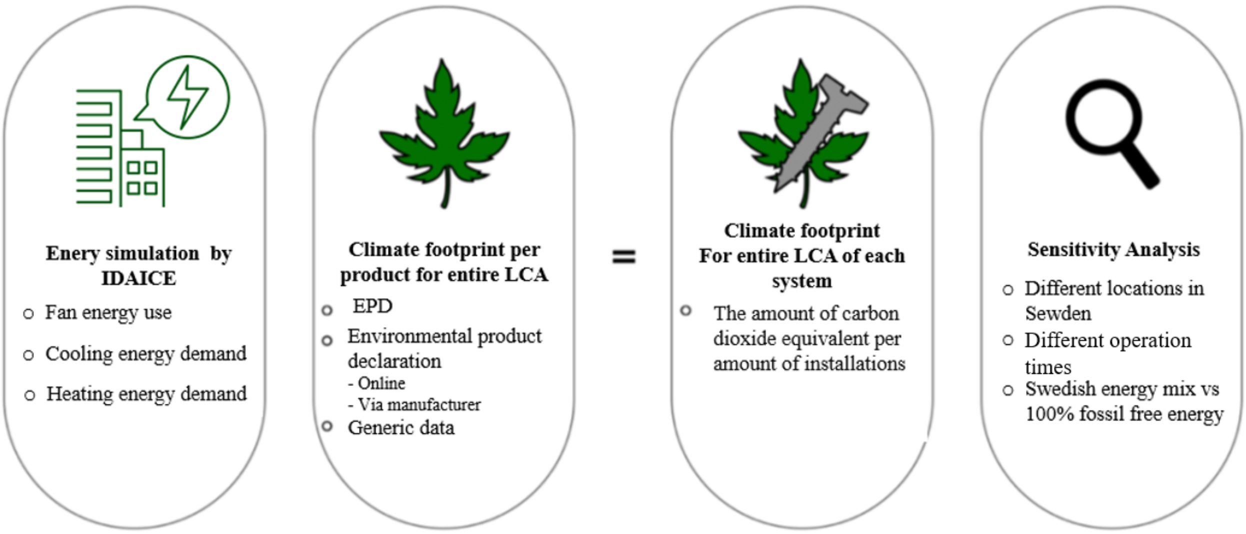

Figure 11: Calculation method for current project.

By using the same excel file category, the other stages of life cycle for both systems are added. Moreover, during current project, if in reference study, an EPD was not in accordance with EN 15804+A2, it was tried to replace with the updated version or at least an EPD from a similar produce. Table 14 shows the products that their EPD was updated during current project. Thermal Insulation EPDs, although was in accordance with EN 15804:2012+2013: A1, was not updated because in the EPD it is mentioned that biogenic carbon is not covered by GWP (Saint-Gobain Denmark A/S, 2020).

Table 14: List of products that their LCA data was updated to EPD.

Product / Module	Reference study				Current study			
	A1-A3	**A4**	**A5**	**Old database**	**A1-A3**	**A4**	**A5**	**Database**
	kg CO_2e /(kg) or (per product)				kg CO_2e /(kg) or (per product)			
Chilled beams	3.10614	0.08	-	Componentized	85.5	1.01	-	(environdec.com, 2023)
AHU for ACB	19100	424	-	epd-norge.no Luftbehandlingsaggregat, Ventistål - eQ50	10700	64.6	-	(environdec.com, 2024b)
AHU for VAV	19100	424	-	epd-norge.no Luftbehandlingsaggregat, Ventistål - eQ50	16200	101	-	(Swegon, 2024)
Manual Damper	3.1	0.08	-	Generic Finnish database	4.07	0.0101	-	(EPDhub.com, 2024b)
Louvres - metal coated steel	2.6	0.08	-	Componentized	3.72	0.0464	-	(EPDhub.com, 2023a)
VAV diffuser	3.1	0.08	-	Componentized	7	0.0244	-	(EPDHUB, 2022)
Circular ducts	3.32	0.0468	3.32	EPDhub/ EPD Lindab - Lindab Safe & Safe Click	2.75	0.0275	0.013	(EPDhub.com, 2024a)
Circular fittings	3.32	0.0468	3.32	EPDhub/ EPD Lindab - Lindab Safe & Safe Click	3.59	0.0853	-	(EPDhub.com, 2023c,)
Rectangular Ducts	3.1	0.08	-	Generic Finnish database	2.97	0.0852	-	(EPDhub.com, 2023d)
Rectangular Fitting	3.1	0.08	-	Generic Finnish database	3.59	0.0853	-	(EPDhub.com, 2023e)

The results of A1-A5 after updating mentioned EPD are shown in Figure 12. Finally, for knowing the uncertainty of used data, another analysis is done, to see how much results for A1-A5 modules are changed by updating calculation database compared to reference study.

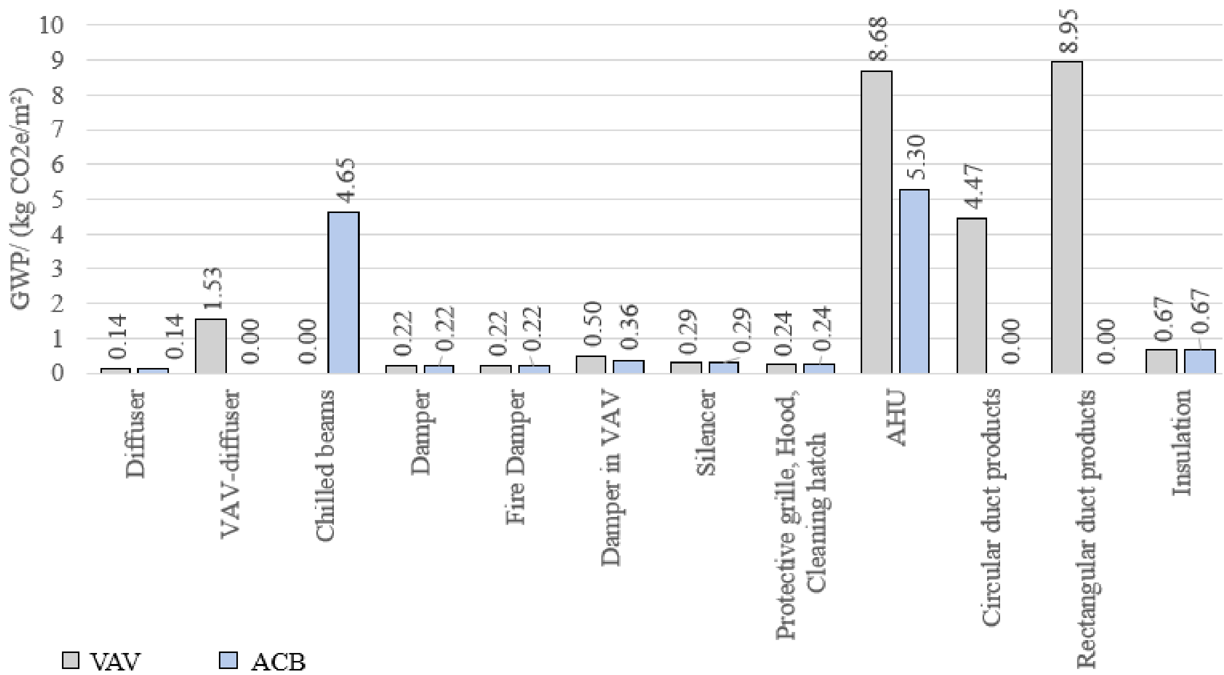

Figure 12: Current project results after updating data

Use Stage Calculation

For calculating use stage, a study service time is needed to be defined (Boverket, 2019b). The main active electronic part in an HVAC system, which is AHU, usually lasts 20-25 years. In Swegon's EPD for Golden RX AHU, for example, the service time of AHU is considered as 20 years (Swegon Operational AB, 2024). In this study, to avoid neglecting the impact from replacement by considering 20 years as study service time, 25 years is considered as study service time.

B2 maintenance

Changes in system performance during its service lifetime will make a maintenance control to keep the performance in the highest level (Chen, 2011). Main maintenance of HVAC Systems involves visual inspection and sensible correction (Aherne, 2009), which does not contribute to climate change during these investigations (Chen, 2011). In Sweden, periodic maintenance inspection which called OVK, a mandatory ventilation control, is usually done for being sure about the airflow of the ventilation system, as it is intended (Boverket, 2024).

As it was mentioned earlier, cleaning is also considered as maintenance (Boverket, 2019). Dust can be a reason for changes in intended airflow. AHU's filters in the inlet protect heat exchanger and provide fresh air, and the filter on the outlet aims to protect the heat exchanger from dust, flies, etc. Changing filter every year aims to keep the whole system clean but over years cleaning might be needed (Lindab,2024). In this study only the energy that is used for cleaning process of HVAC system is considered for maintenance.
In EN 15780, office spaces quality category is considered as medium quality and based on this quality category (SS EN 15780:2011, 2011), cleanliness inspection intervals for different parts of ventilation systems are usually done based on the Table 15.

Table 15: Medium Quality class cleaning intervals, Source: (SS EN 15780:2011, 2011)

Quality class	AHU	Filter	Ducts	Terminals
Medium for office rooms	12 months	12 months	24 months	24 months

EN 15780 recommends that for filter's interval it is better to check the manufacturer instructions. Based on this standard there are different evaluation methods to find dust level in ventilation systems that is out of the scope of this study. Additionally, filters status can be a good sign for a cleaning call(SS EN 15780:2011, 2011). In Appendix D, cleaning actions and plans of different parts of the ventilation system is shown (SS EN 15780:2011, 2011).

As Assemblin said Priorn building's ventilation system has not been cleaned from 2018 after it started using (Barnekow, 2024) . Therefore, an assumption should be made for cleaning time, in consultation with Lindab's experts, it was assumed that the cleaning process of HVAC system in this building might occur based on the data shown in Table 16.

Table 16: Assumption for HVAC cleaning in Priorn building source: (Lars-Åke Mattsson, 2024)

Cleaning Interval	Process time	Cleaning equipment	Collecting duct equipment
Every 10 years	12 hours	Lifa Air Special Cleaner 25 Multi Brushing Machine for HVAC Cleaning, 0,75 kW(Lifa-air.com, 2024)	Lifa Air HepaClean 3500 Negative Pressure Unit (NPU) For Dust Control, 0,78 kW(Lifa-air.com, 2024)

B4, replacement

For calculating B4 module, based on the SS-EN 15804+A2, the production of new product (A stage), and the demolition of removed product (C stage) should be added up, and multiply by the replacement number, as it is shown in equation 2. In this calculation, it is assumed that the new replaced products are from the same manufacturer as removed one.

$$B4 = (A\ stage\ new\ product + C\ stage\ removed\ product\ )x\ (replacement\ number)$$

(2)

The replacement time shown in equation 3, to ignore the impact of A stage in this calculation the result of division must be subtracted by one.

$$Replacement\ number = (Studied\ service\ lifetime\ \div\ product\ service\ lifetime) - 1$$

(3)

Replaced components in ACB system is shown in Table 17. After calculating equation 3, the results for replacement number are rounded up.

Table 17: Replacement number in ACB components

Category in ACB	Component	Service lifetime	Replacement number over 25 years
Room Units	Dampers	20 years	1
AHU	AHU	20 years	1
	Filter	1 years	24
Fire dampers	Fire dampers	20 years	1

In VAV system, those components that has a lower life span compared to the study lifetime are shown in Table 18.

Table 18: Replacement number in VAV components

Category in VAV	Component	Service lifetime	Replacement number over 25 years
Dampers	VAV dampers	20 years	1
Fire dampers	Fire dampers	20 years	1
AHU	AHU	20 years	1
	Filter	1 years	24

B6, Operational energy use

In this study, the operation of fan in HVAC system and heating and cooling used in building is calculated during their operational time of ACB and VAV systems. For calculation of GWP $_{fossil}$ emitted by B6 module the following equation is used:

$$GWP\ of\ \ B6\ per\ year\ = Energy\ use\ (kWh/m^2.year)\ .value\ of\ GWP\ from\ source\ of\ energy (kg\ CO_2e/kWh)$$

(4)

By multiplying the equation 4 by study service lifetime, the GWP $_{Fossil}$ emitted during service lifetime is calculated. The energy carrier of this operation shown in Table 10. In this study GWP $_{fossil}$ from B6 module is assumed to be emitted from heating, cooling, and fan energy use of Priorn building over 25 years.
A scenario of future green energy also is studied to compare the systems in the future that Sweden will have fossil free energy by 2050 (Boverket, 2019b). Moreover, a scenario of changing geographical locations is also assessed for this module. For both scenarios two types of databases is used to assess the certainty of results. The other used energy during production or end of life processes are excluded for in future target scenario.

End-of-life Stage

Since Finnish generic data does not cover C stage, inevitably a componentized method is used for those products that this database was used for their A stage. See Table 19-20 for input of C stage based on products category.

Table 19: Componentized used data, Source: (environdec.com, n.d.; Environdec.com, 2024; environdec.com, 2024a; EPDhub.com, 2023c)

EPD	Product Category	C1	C2	C3	C4
Steel	Cooling pipes, Duct fan, Fan convector	0.00559	0.00436	0.0255	0.000264
Copper	Cooling pipes, Fan convector	0	0.0174	0.000101	0
Aluminium 0% scrap	Diffusers, Dampers, Protective grid, Fan convector	0	0.0188	0.0213	0.00745
Aluminium 75% scrap	Outer wall Protective grid, Diffusers	0	0.0133	0.0203	0.00133

The other products have their own EPD or similar EPD for their C stage, See Table 20.

Table 20: C stage value of products with EPD

Category	Product	C1	C2	C3	C4	EPD source
		GWP/(kg CO_2e / (kg or piece of product))				
Damper	Flow Damper	0.0437	0.00488	0.123	0.000253	(EPDhub.com, 2024b)
VAV-dampers	VAV dampfer DCV-CF/BL	0	0.00569	0.367	0.0181	(EPDhub.com, 2023b)
	DCV-CF/BL (JSPM)	0	0.00334	0.102	0.138	(EPDhub.com, 2022)
	Dampers DCV-RC	0	0.00569	0.367	0.0181	(EPDhub.com, 2023b)
Fire Damper	EKO-SRBG EKO-SRB	0	1.47	0.829	0.0402	(EPhub, 2022)
	EKO-JBG2	0	0	0.829	0.0402	(EPhub, 2022)
YG, Protective grill, Hood, Cleaning hatch	EKO-NR	0.0046	0.00437	0.0208	0.000263	(EPDhub.com, 2023a)
AHU	AHU in VAV	1.06	27.50	113.00	30.14	Not varified EPD (swegon, 2024)
	AHU in ACB	0.645	16.7	90.7	18.7	(environdec, 2024b)
Circular duct products	Circular ducts	0.00495	0.00376	0.0337	0.000944	(EPDhub, 2023e)
	Cicular fittings	0	0.00363	0.156	0.000253	(EPDhub.com, 2023e)
Rectangular duct products	Rectangular ducts	0.0033	0.00454	0.0271	0.000263	(EPDhub.com, 2023d)
	Rectangular fittings	0	0.00363	0.156	0.000253	(EPDhub.com, 2023e)
Insulation	Thermal insulation	0	0.00665	0	0.0181	(EPD-norge.com, 2022;)
	Sound and fire insualtion	0.0106	0.00320	0	0.0139	(EPD-norge.com, 2022;)
Chilled beams	Parasol 1200 LF/MF/HF/PF	0.00753	0.199	0.0508	0.0553	(environdec.com, 2023)

4.4.4 Limitation of calculation

In this study and reference study the main obstacle to conduct the LCA calculation was lack of data for building installations. Being not covered by climate declaration rules is the main reason of lack of generic data and EPD for building installations (Abuayyash, et al; 2024; Boverket, 2019). Therefore, several assumptions need to be made, which can make uncertainty in results.

4.5 Data inventory for A1-A5

As it was mentioned earlier, three data inventory principles were used for climate calculations. Tables 24 and 25 are provided for both ACB and VAV systems to define which database is mostly used for LCA calculation. In order to assess the uncertainty of results in A1-A5 modules, both generic data and componentized approaches considered as assumption.

4.5.1 Production and construction stage of VAV

The data inventory used for VAV components is shown in Table 21.

Table 21: data inventory of reference study of VAV system compared to current study.

Category	Product	Database used for (A1-A5)	Status in current study
Dampers	Manual damper (Circular)	Generic data	Updated EPD
	Fire damper (Circular)	EPD	EPD from other manufacturers
	Fire damper (Rectangular)	EPD	
	VAV damper rectangualr	EPD	
	VAV samper circualar	EPD	Some of products used other manufacturer EPD
	Manual damper (Rectangular)	Componentized	
Products with Factory-Installed Insulation	Sound damper (circular / recrangular)	Generic data EPD	EPD was used only for insulation part of these products.
	Roof penetration	Generic data EPD	
	Over air device	Generic data EPD	
	Filter cabinet	Generic data EPD	
Exterior Wall and Protective Grilles, Exhaust Hood, Cleanout Door, and Backdraft Damper	Circular protective grid	Generic data	
	Rectangular protective grid	Componentized	
	Wire mesh louvre	Generic data	
	Cleaning hatch	Generic data	
	Exhaust air hood	Generic data	
	Check valve	Generic data	
Air Distribution Components	Nozzle	Generic data	
	Air Supply Unit	Componentized Generic data	Only Products from Klimatbyrån are componentized
	Air Box	Generic data	
	Air Inlet	Generic data	
	Air Vent	Generic data	
	Exhaust Unit	Componentized Generic data	Only Products from Klimatbyrån are componentized
Ductwork	Circular duct	EPD	is updated due to published EPD
	Circular fittings	EPD	is updated due to published EPD

	Rectangular ducts	Generic data	is updated due to published EPD
	Rectangular ducts	Generic data	is updated due to published EPD
Insulation	Thermal insulation	EPD	is updated due to published EPD
	Fire and sound insulation	EPD	
AHU	Supply air fan	Generic data EPD	Replaced by Swegon Similar AHU. Updated EPD
	Exhaust air fan	EPD	
	AHU	EPD	
	Heating coil	Generic data	
	Cooling coil	Generic data	
	Filter cassette	Generic data	
	air cleaner	EPD	

4.5.2 Production and construction stage of ACB

The data inventory of ACB system is shown in Table 22.

Table 22: Data inventory of reference study ACB system compared to current study.

Category	Product	Database used for (A1-A5)	Status in current study
Dampers	Manual damper (Circular)	Generic data	Updated EPD
	Fire damper (Circular)	EPD	EPD from other manufacturers
	Fire damper (Rectangular)	EPD	
	VAV damper rectangualr	EPD	
	VAV samper circualar	EPD	Some of products used other manufacturer EPD
	Manual damper (Rectangular)	Componentized	
Products with Factory-Installed Insulation	Sound damper (circular / recrangular)	Generic data EPD	EPD was used only for insulation part of these products.
	Roof penetration	Generic data EPD	
	Over air device (exhaust air)	Generic data EPD	
	Filter cabinet	Generic data EPD	
Exterior Wall and Protective Grilles, Exhaust Hood, Cleanout Door, and Backdraft Damper	Circular protective grid	Generic data	
	Rectangular protective grid	Componentized	
	Wire mesh louvre	Generic data	
	Cleaning hatch	Generic data	
	Exhaust air hood	Generic data	
	Check valve	Generic data	
Air Distribution Components	Nozzle	Generic data	
	Air Supply Unit	Componentized Generic data	Only Products from Klimatbyrån are componentized
	Air Box	Generic data	
	Air Inlet	Generic data	
	Air Vent	Generic data	
	Exhaust Unit	Componentized Generic data	Only Products from Klimatbyrån are componentized
	Chilled beams	Componentized	Replaced by Parasol from Swegon
	Piping	Generic data	
Ductwork	Circular duct	EPD	are updated due to published EPD
	Circular fittings	EPD	
	Rectangular ducts	Generic data	
	Rectangular ducts	Generic data	

Insulation	Thermal insulation	EPD	
	Fire and sound insulation	EPD	
AHU	Supply air fan	Generic data EPD	Replaced by Swegon Similar AHU. Updated EPD
	Exhaust air fan	EPD	
	AHU	EPD	
	Heating coil	Generic data	
	Cooling coil	Generic data	
	Filter cassette	Generic data	
	Air cleaner	EPD	

4.6 Data inventory for B6

B6 module is calculated based on the different database, to do a sensitivity analysis explained under next section. Firstly, As mentioned earlier, Boverket provided average values for both electricity and district heating for the whole country to avoid complexity in calculation. See Table 23.

Table 23 : Swedish average values for electricity and district heating, Source: (Boverket, 2022)

GWP $_{fossil}$ emission/ (kg CO_2 e/kWh)	**Swedish average Electricity**	**Swedish average district heating**
	0.037	0.056

Secondly, the electricity location specific values that are used for B6 calculation is shown in Table 24. The values are used for calculating emission from cooling and fan energy use. The electricity zones are shown in Figure 13.

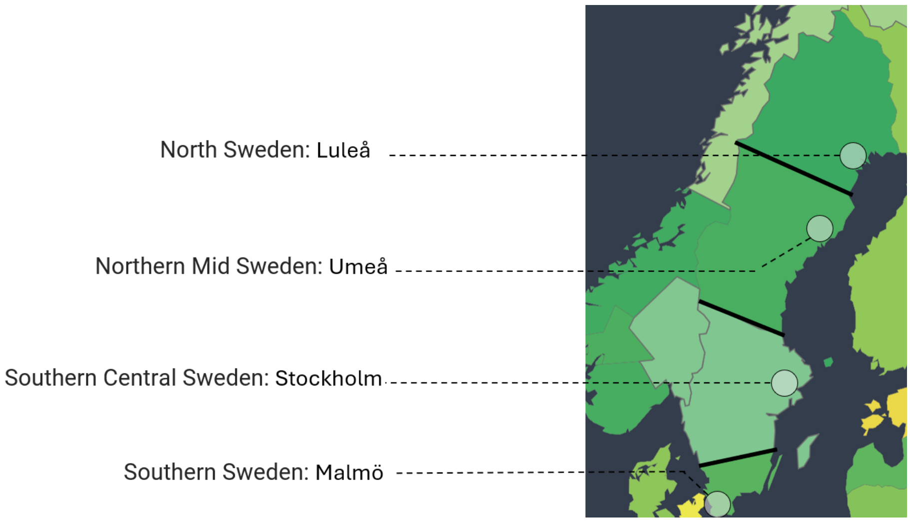

Figure 13: Sweden electricity zones, Source: (electricitymaps, 2024)

Table 24: Electricity location specific GWP fossil values in Sweden. Source: (electricitymaps, 2024)

Electricity zone	**CO2 emission**	**Source of electricity**	**Most populated City in electricity zone**
North Sweden	13 g/ kWh	Wind (22.99%), Hydro (76.28%), Solar (0.02%)	Luleå
North Central Sweden	17g/ kWh	Wind (28.49%), Hydro (69.17%), Solar (0.1%)	Umeå
South Central Sweden	24 g/ kWh	Nuclear (64.01%), Wind (12.44%), Hydro (16.12%), Solar (1.01%), unknown (6.42%)	Stockholm
South Sweden	49 g/ kWh	Wind (61.78%), Solar (5.67%), Hydro (17.98 %), unknown (14.56%)	Malmö

Moreover, district heating providers vary even within a single county (energiforetagen.se, 2023). Therefore, for geographical scenario, most populous cities within each electricity zone are assumed, as they might have higher

GWP fossil emission due to their populations, compared to smaller cities (Farsäter, 2024). See Figure 13. weigh the emissions from all district heating providers, accordingly, as shown in Table 25. The calculation of the emissions from heating in the studied building by applying these weighted values in each location.

Table 25: District heating location specific GWP fossil values in Sweden. Source: (energiforetagen.se, 2023)

Chosen cities	Provider	Network	Delivered energy per year/ kWh	CO_2 emission/ (kg CO_2 e/ kWh)	Weighted CO_2 emission/ (kg CO_2 e/ kWh)
Luleå	Luleå Energi AB	Luleå	$765\cdot 10^6$	0.0254	0.0229
		Luleå klimatneutral	$8.9\cdot 10^7$	0.0012	
Umeå	Umeå Energi AB	Umeå	$8.24\cdot 10^8$	0.554	0.553
		Umeå fossilfri	$1.8\cdot 10^6$	0.0108	
Stockholm	Stockholm Exergi AB	Stockholm	$7.724\cdot 10^9$	0.582	0.582
Malmö	E. ON Energiinfras truktur AB	Industriell spill värme	$3.84\cdot 10^8$	0	0.07
		Residual	$6.22\cdot 10^8$	0.083	
		Särskilt miljöval	$5.5\cdot 10^8$	0.106	

4.7 Uncertainty of data

To account for uncertainty, by calculating how much they are calculated based on assumption and EPD in both projects, the weight of the results in A1-A5 was calculated. This uncertainty aims to shows the results difference between two study after updating database. This uncertainty is done only for A stage results of LCA. This can show how much taken approach toward data selection can be reliable.
Another uncertainty analysis is done for B6 module by using different database as mentioned earlier. The aim of this uncertainty analysis is to assess if the B6 results of two systems for future and across different locations can be reliable.

4.8 Sensitivity analysis of B6

Two types of scenarios are considered for sensitivity analysis of B6 module, the calculation of each analysis is explained here.

4.8.1 Different climate conditions

As mentioned earlier 4 different locations are chosen, including Malmö, Stockholm, Umeå, Luleå, as variable to calculate energy use and operational emission of each ventilation system, these locations are chosen to obtain diverse range of environmental and climatic conditions.
The aim of this sensitivity analysis is to compare the GWP fossil emission from energy use for ventilation systems using two different approaches: Swedish average values and location-specific values for each of the four chosen locations. This comparative analysis aims to clarify how variations in input parameters, particularly location specific data, influence the B6 module.

4.8.2 Future Swedish climate target

In alignment with Sweden's goal of decarbonization the grid by 2050 (UNEP, 2023), another analysis is done based on the Boverket's average values and location specific values emphasized on considering a future scenario when calculating B6 module, to make certain that used climate data is in accordance with Sweden's climate target (Boverket, 2019b). At the moment, Sweden is working creating a dynamic climate data for future energy carrier (Boverket, 2019b), therefore due to the lack of this data, by considering an equal yearly reduction between current year which is 2024, and 2050, a dynamic climate data is assumed. And finally, the sensitivity of results for each year between 2024 and 2050 is calculated, by considering that the study service time is 25 years.

4.8.3 Fan operation schedule

In the base scenario of this study, the fans of two systems operate during different times, ACB's fan operates only during working hours, while VAV's fan operates always while during unoccupied hours the minimum airflow is supplied. Two other scenarios are assessed to see the performance of results, if both systems' fans operate during the same schedules, including, being off during unoccupied hours and always on even during unoccupied hours.

5 Results

In this section, results of energy simulations, GWP $_{fossil}$ from energy simulations, LCA are explained, and uncertainty of data for A1-A5 finally a sensitivity analysis with focus on B6 results are explained.

5.1 Energy simulation

The results of energy simulation for the case study with a VAV system compared to the reference values from MVB company are shown in Table 26.

Table 26: Energy simulation results compared to reference results from MVB AB.

Energy parameter	Reference value/ (kWh/ (m^2 · year))	Simulation result/ (kWh/ (m^2 · year))
Heating energy use	11.4	10
Fan energy use	8.8	8
Cooling energy use	2.4	2

A comparison between total energy use of the case building, using Malmö weather file is shown in Figure 14. Although fan and heating have a larger share in a VAV, 8 and 10 (kWh/(m^2.year)) respectively, having ACB as a ventilation system in building resulted in higher cooling energy consumption equal to 4 (kWh/(m^2.year)), compared to VAV which is 2 (kWh/(m^2.year)).

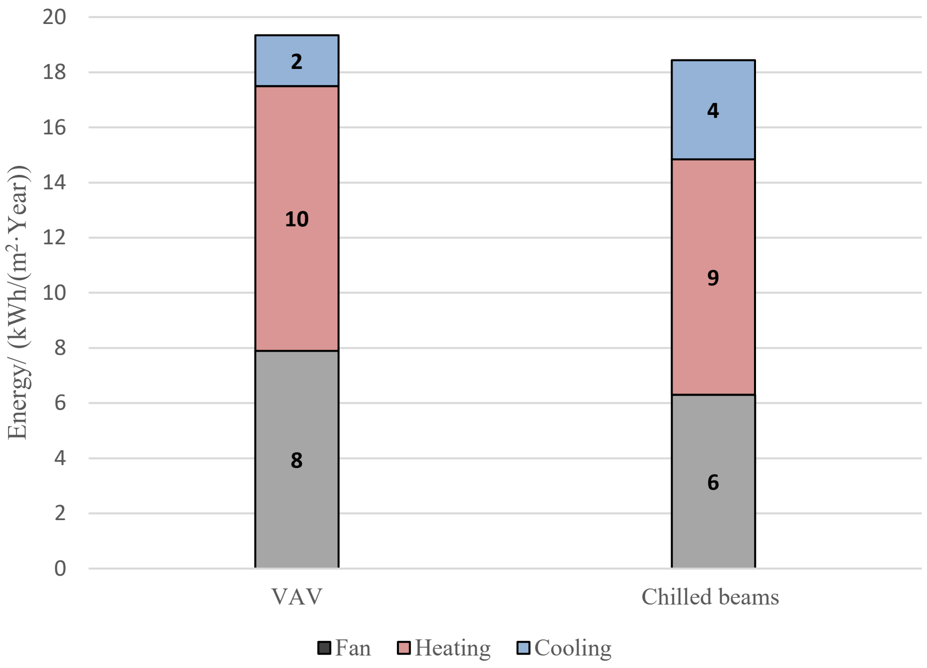

Figure 14: Total energy use case building for VAV compared to ACB system.

As mentioned earlier, energy simulation was done 4 times, by changing weather files in IDA-ICE, see Figure 15. As can be seen chilled beams across all the locations consume lower energy compared to VAV systems, while in Malmö and Stockholm the difference between VAV and ACB is insignificant compared to their differences in Umeå and Luleå.

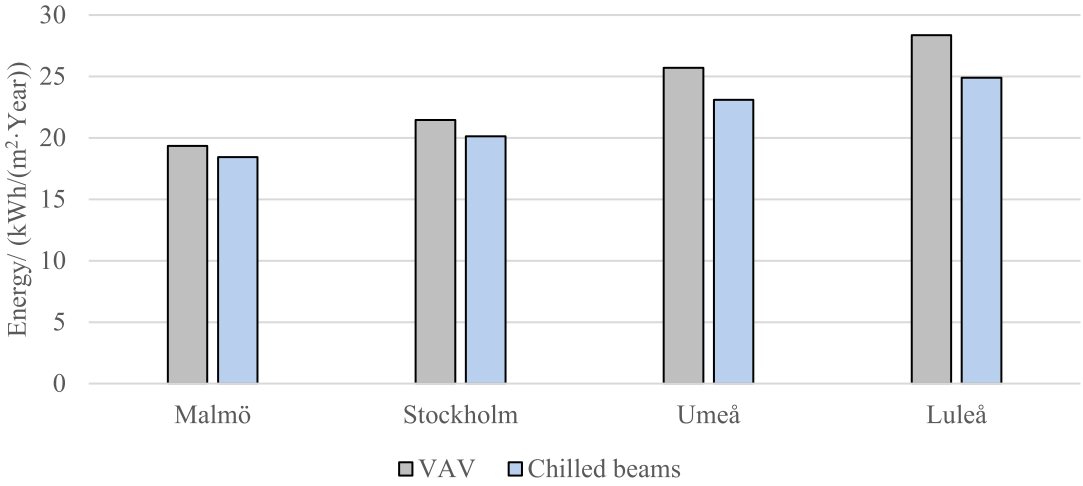

Figure 15: Energy use comparison in 4 different locations.

By breaking the results into fan, heating, and cooling energy use, as shown in Figure 16, the highest energy use relates to heating for both systems across all the locations. While ACB resulted in a lower heating energy use in case building compared to VAV, the colder the location, the higher heating energy use it has. On the other hand, cooling energy use has the lowest contribution across all the cities. Meanwhile, the ACB consistently has the highest results for cooling compared to VAV. It can also be seen that fan energy use for chilled beams is almost the same in all the locations due to the constant airflow. While for VAV it has a rising trend by going into the northern locations.

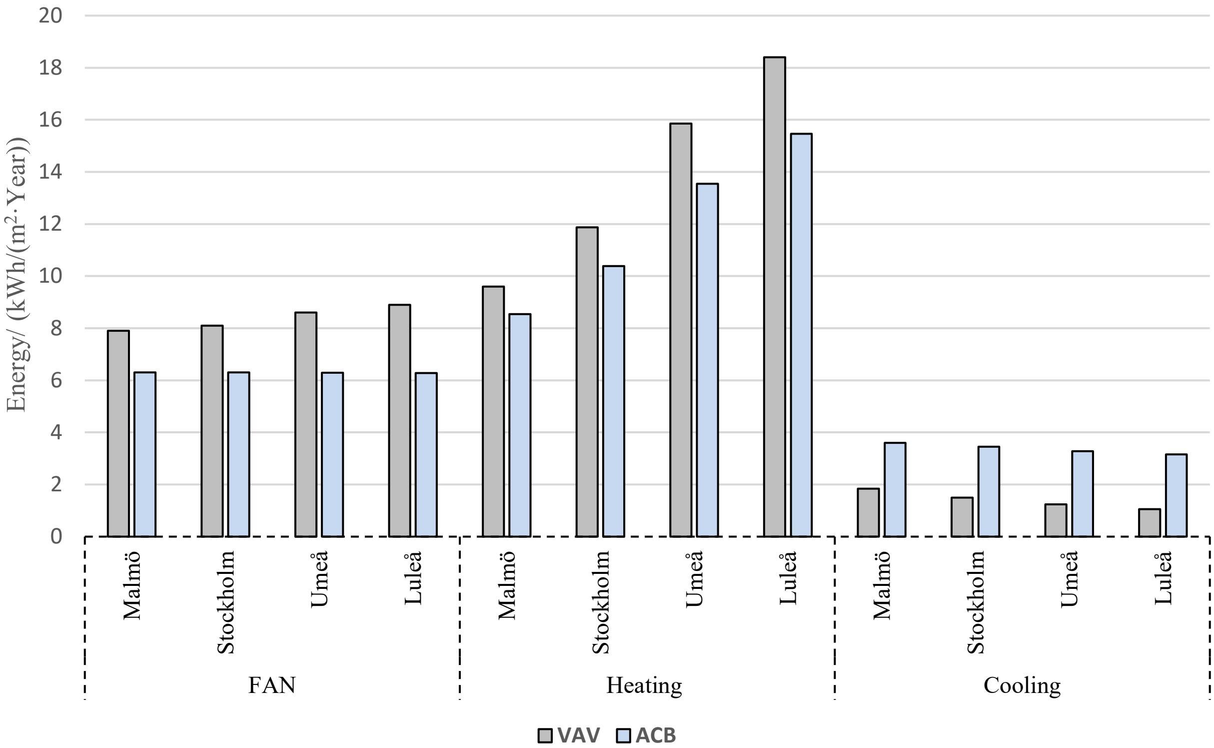

Figure 16: Fan, heating, cooling energy use in different geographical scenarios.

5.2 LCA results

5.2.1 Embodied GWP $_{fossil}$

Embodied GWP $_{fossil}$ includes A stage, B2 and B4 modules and C stage. In these results B2 and B4 are considered as a joint unit. The results of embodied GWP $_{fossil}$ for both systems are shown in Figure 17. For 25 years, ACB contributes to a lower embodied GWP fossil compared to VAV in all the stages. While for both systems, embodied GWP fossil A stages contribute to largest share.

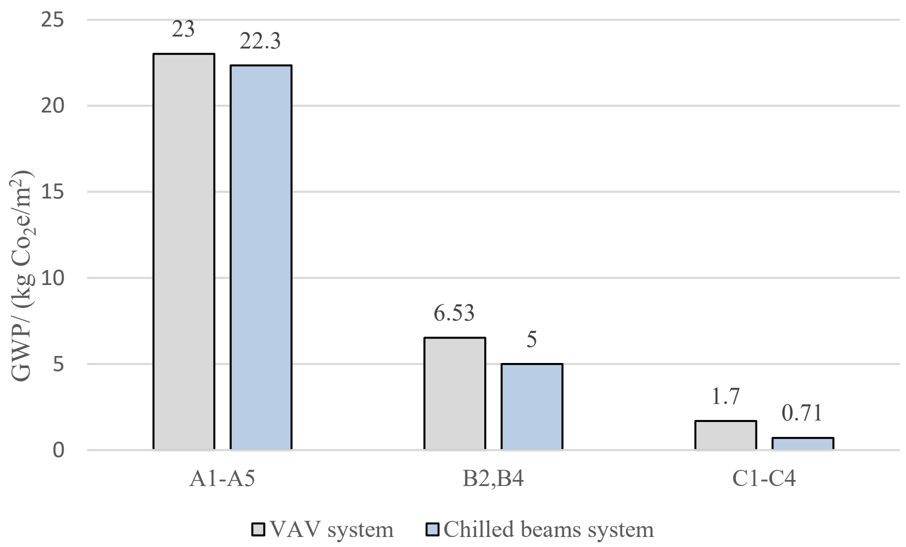

Figure 17:Embodied GWP-fossil over 25 years.

The products that contribute to GWP fossil in B4 module are shown in Figure 18. AHU in both systems have the highest emission.

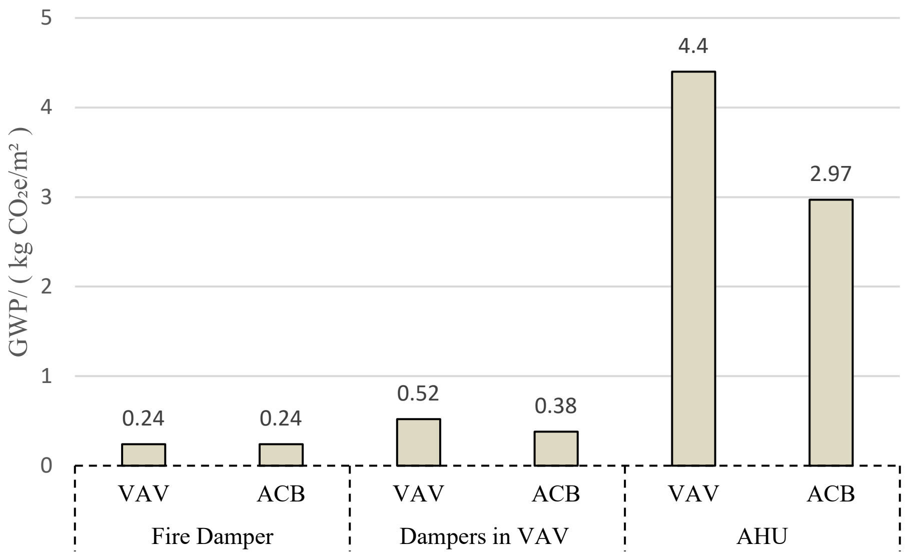

Figure 18: Replaced components over 25 years

5.2.2 Operational GWP fossil

The results of operational GWP fossil over 25 years for both systems are shown in Figure 19. The VAV has a higher GWP fossil impact compared to ACB. The higher total energy use that a system has, the higher contribution it has in GWP fossil. The results are shown for Malmö climate file and Swedish average values.

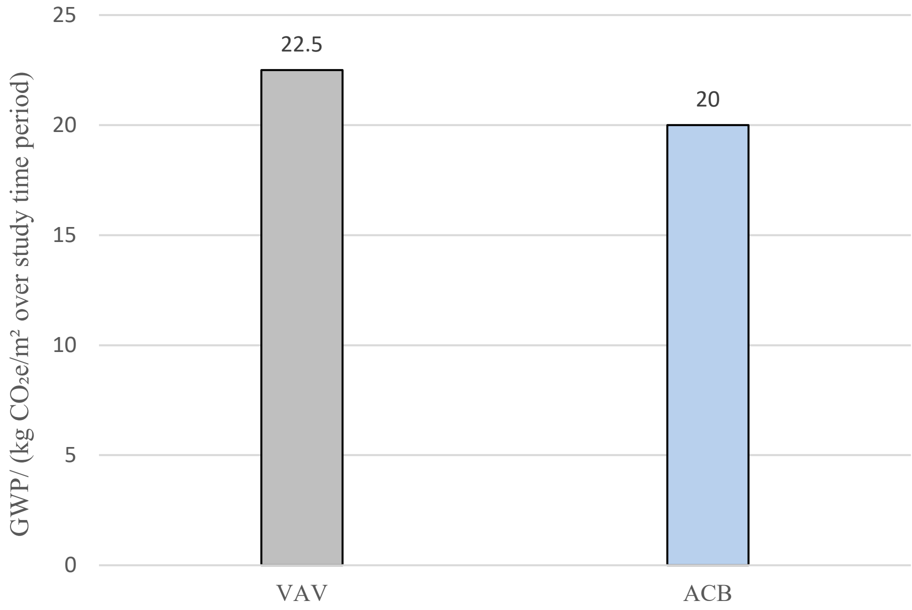

Figure 19: Operational GWP fossil in VAV and ACB

5.2.3 Entire Life cycle assessment

Figure 20 shows that VAV has higher results in an entire life cycle approach compared to ACB system. The following figure shows the results in 25 years. Considering an entire life cycle perspective, shows that B stage includes B2, B4 and B6 modules, and has the highest contribution in both systems.

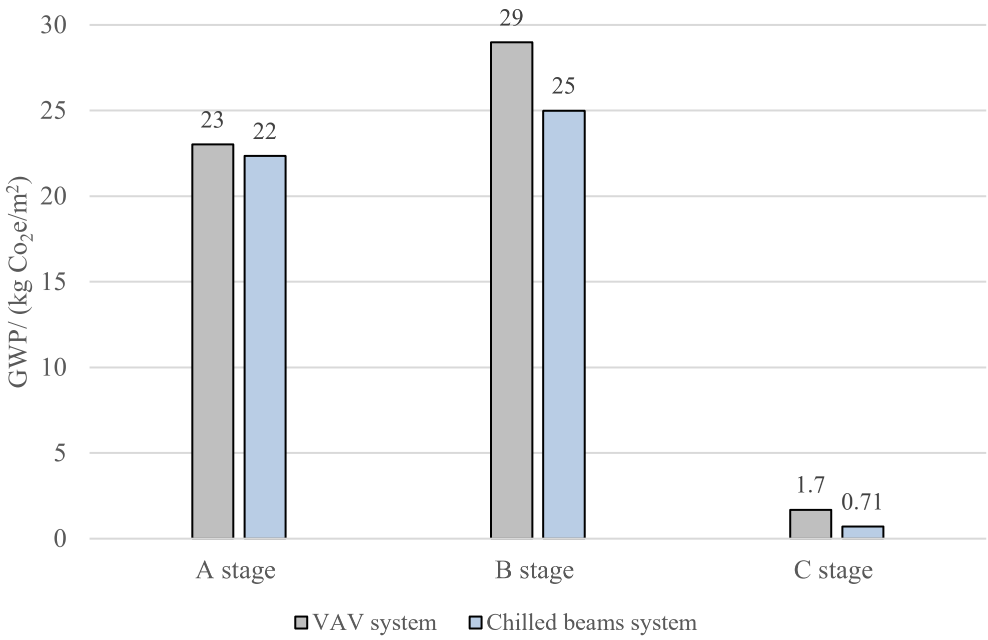

Figure 20: Entire LCA of both systems.

Figure 21 shows, over 25 years, the contribution of B stage for VAV is 53.6%, while in ACB, B stage's share equal to 51.5%. On the other hand, the lowest share for both systems relate to C stage, 3.2% for VAV and 1.5% for ACB. Regarding A stage, in VAV the emission from A stage is 43.3% while in ACB stage share a contribution equal to 47%.

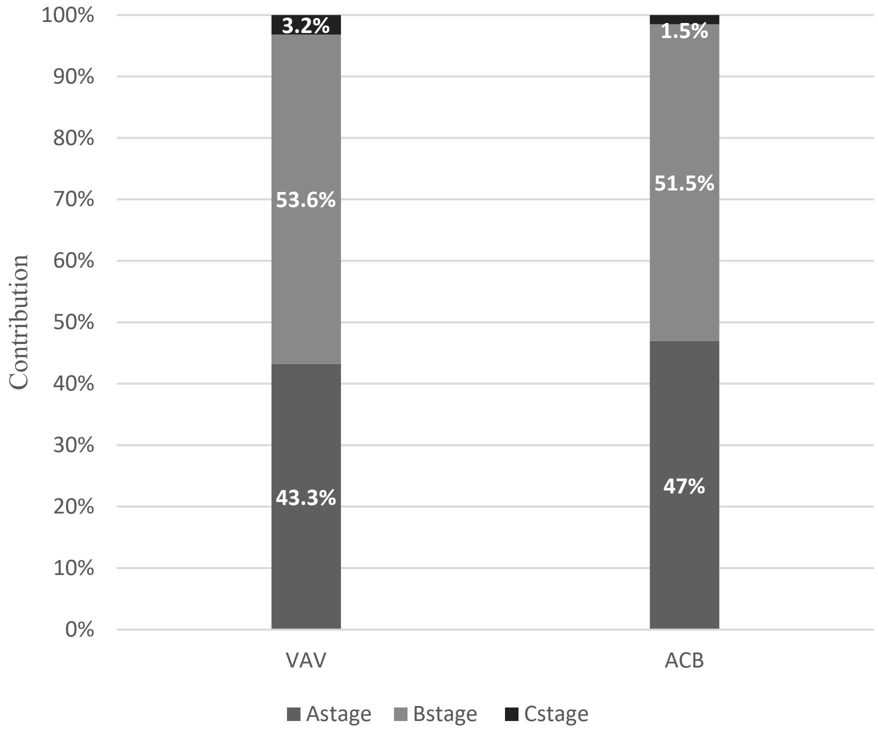

Figure 21: LCA stage's contributions in both systems.

5.3 Uncertainty of data

By Replacing new EPD or new similar EPD from other manufacturers, instead of those generic data and componentized calculations, new results of A1-A5 are calculated. As it can be seen Figure 22, results for both systems are lower than when making assumptions in reference study. While The difference between two systems become higher.

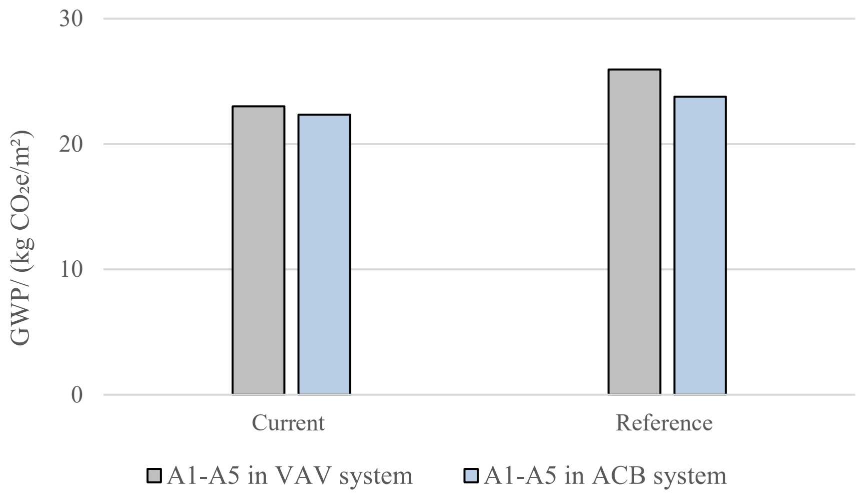

Figure 22: A stage results in both current and reference study.

As it can be seen in Figure 23, almost half of the data used in reference study for VAV is made by assumption, while in current study almost 96% of used data for calculation A1-A5 is from valid EPD. The contribution of assumption in ACB in reference study is more than 80%, while in current study almost 88% of used data is from EPD.

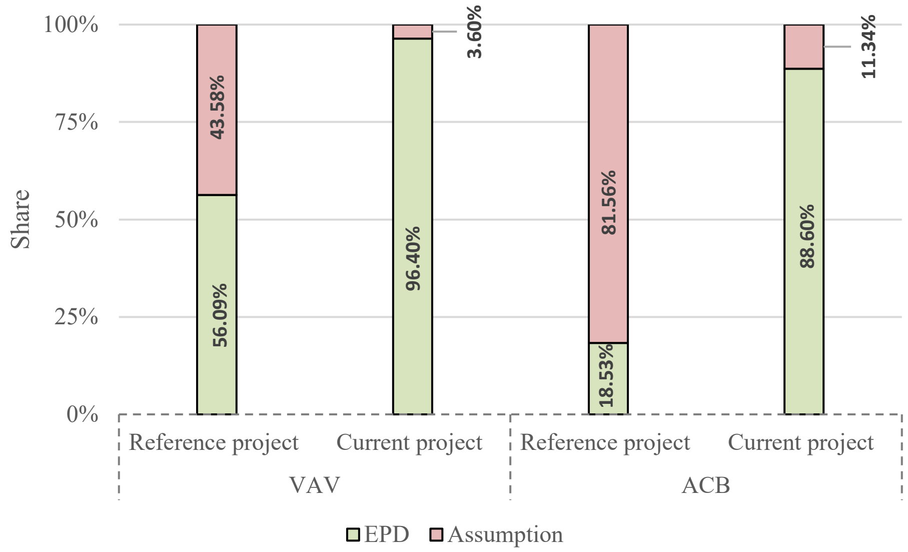

Figure 23: share of assumption and EPD in A stage results.

5.4 Sensitivity analysis results

The results of sensitivity analysis for different weather conditions, and future Swedish climate target is explained in the following sections.

5.4.1 Different climate conditions

This sensitivity analysis is done by considering 2 types of databases for GWP $_{fossil}$ emission from energy sources, including Swedish average data and location specific data. Figure 24 shows the GWP $_{fossil}$ emission from B6 for selected cities, using Swedish average values and location specific values. It can be seen that GWP $_{fossil}$ emitted from operational energy in Umeå and Stockholm have a significant difference by changing database. In these two cities, Swedish average values resulted in lower emission compared to location specific GWP $_{fossil}$. On the other hand, in Malmö and Luleå, the gained results by location specific values are lower than Swedish average values. See Figure 24.

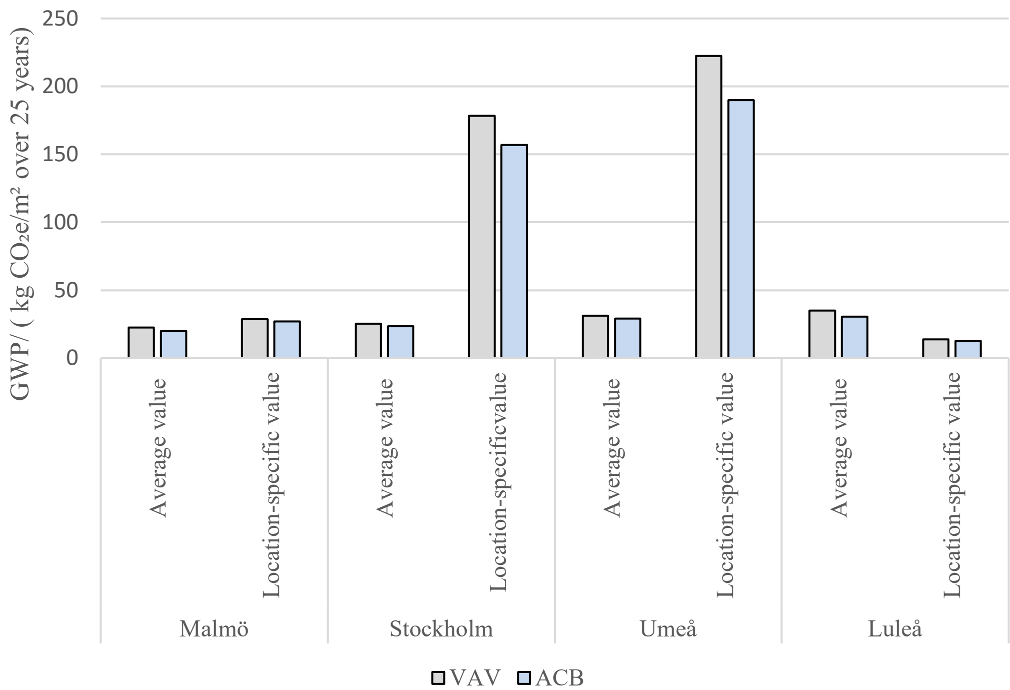

Figure 24: Comparison between total GWP fossil by using average values and location specific values.

Taking a detailed look on each city, shows that in Malmö, the difference between district heating's average and location specific values is higher than electricity database. In other word, average electricity values for electricity are closer to the Malmö-specific values, as it can be seen that fan and cooling results have a lower difference. See Figure 25.

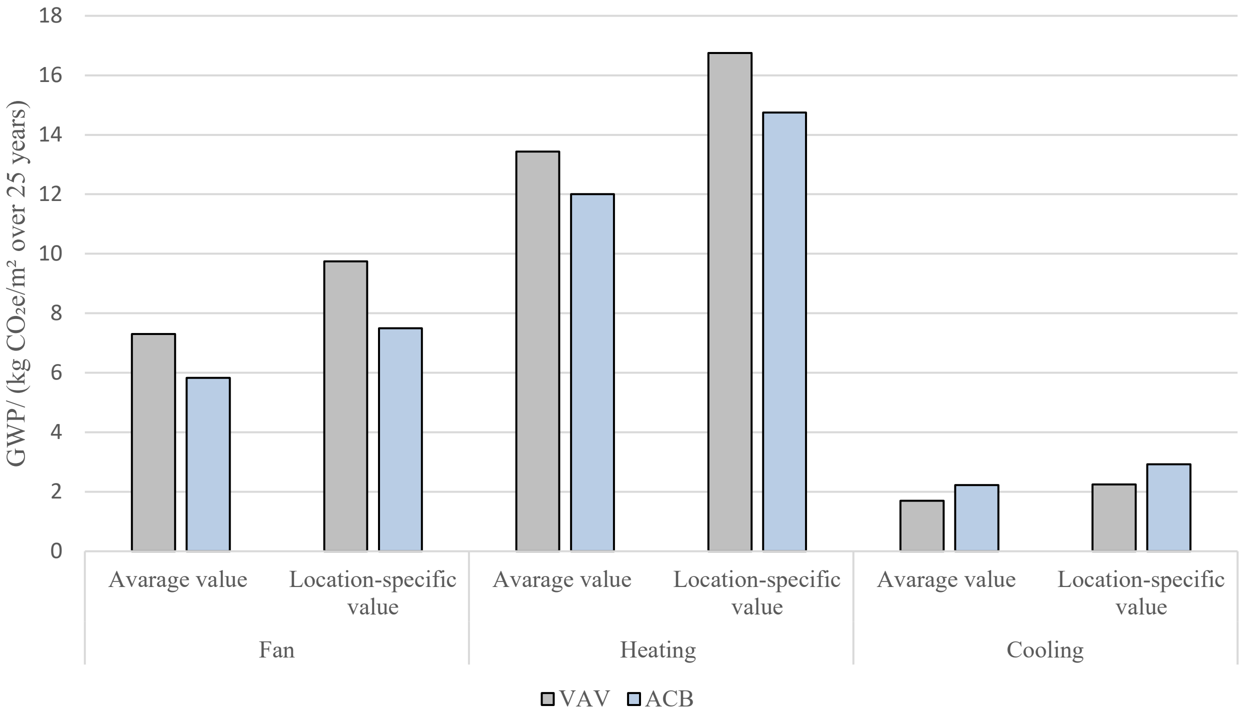

Figure 25: GWP fossil emission from different energy use by considering average values and Malmö specific values.

In Stockholm, the difference between GWP $_{fossil}$ emission for heating in both systems, has a higher difference by using average values instead of location-specific values. In other words, by using average district heating values for Stockholm, GWP $_{fossil}$ emission is lower than the values which is expected to be. GWP fossil emission by both average electricity value and location-specific values have insignificant difference. See Figure 26.

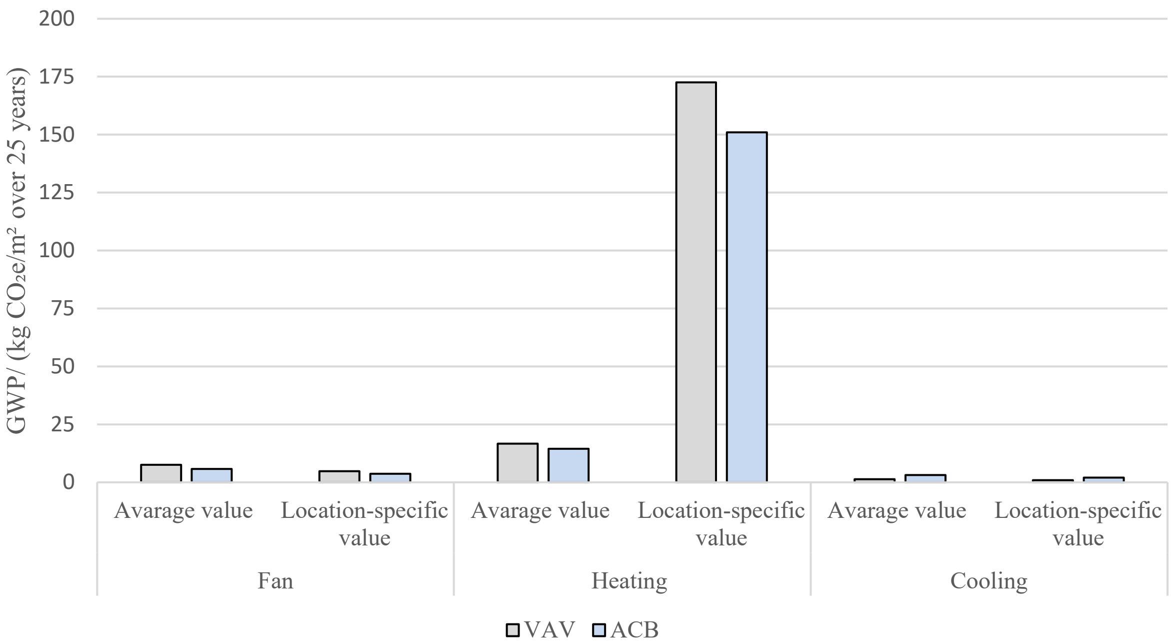

Figure 26: GWP fossil emission in Stockholm, comparing average values and location specific values.

In Umeå, like Stokholm, emission from heating in both systems, has a significant different when using average value instead of location-specific values. The district heating average value shows lower GWP $_{fossil}$ emission compared to location specific values. See Figure 27.

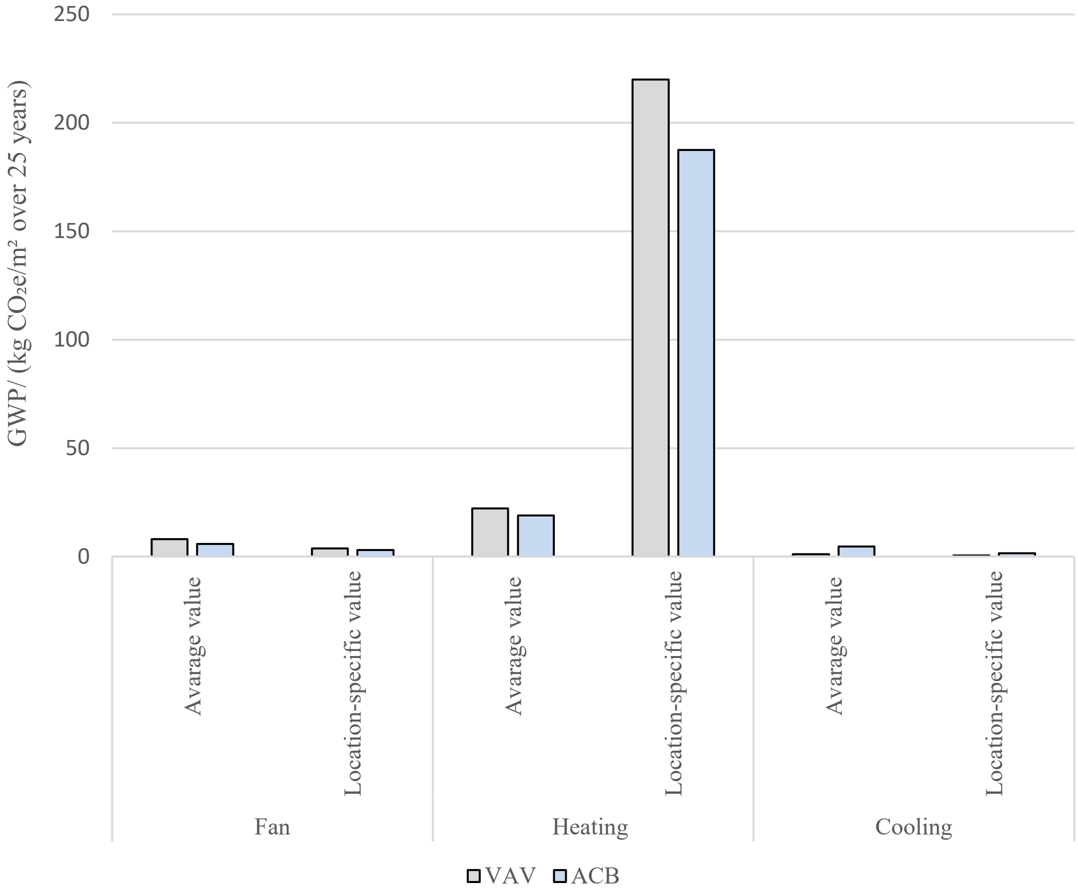

Figure 27: GWP $_{fossil}$ emission in Umeå , comparing average values and location specific values.

In Luleå, district heating's location specific values resulted in a lower GWP $_{fossil}$ emission compared to district heating average values. In addition, the electricity GWP $_{fossil}$ emission in Luleå results in lower figures compared to electricity average values. See Figure 28.

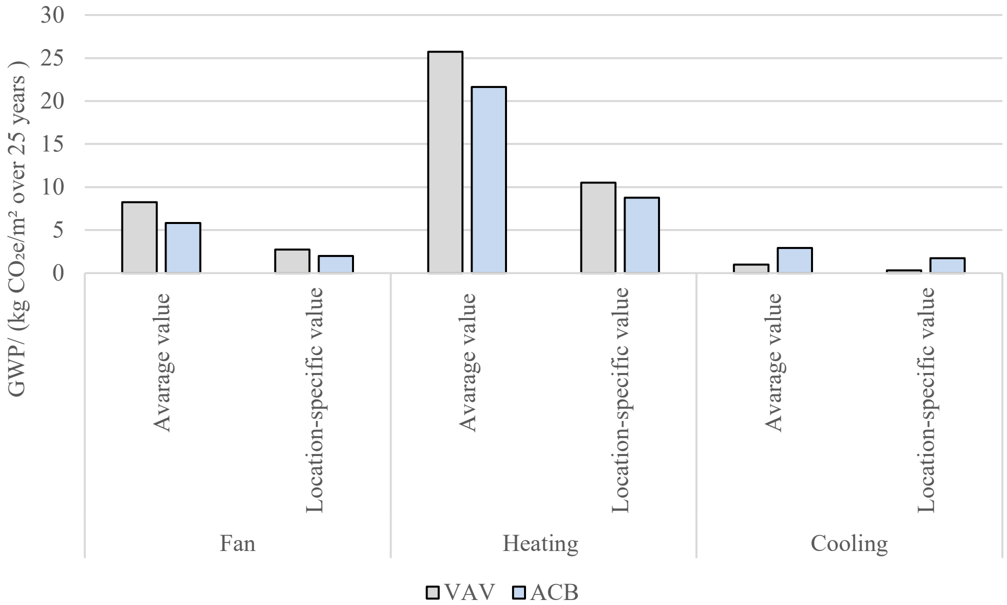

Figure 28: GWP fossil emission in Luleå , comparing average values and location specific values

5.4.2 Future Swedish climate target

Regarding Swedish fossil free energy target, Figure 29 shows the GWP $_{fossil}$ emitted by operational energy, by using average values, in both systems with future energy carriers will have the same emission and low, regardless of location.

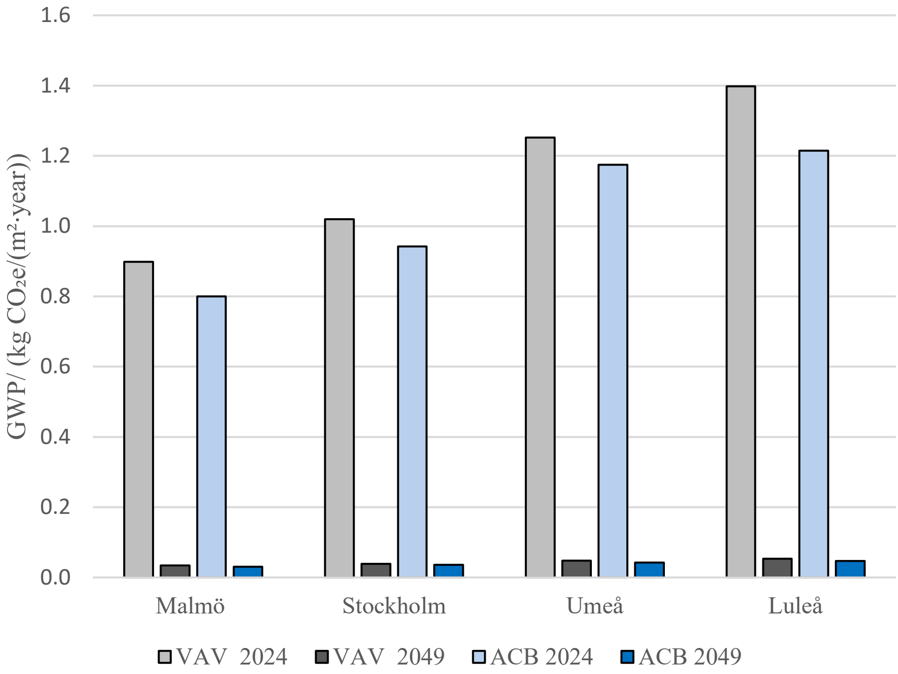

Figure 29: GWP fossil emitted by Operational energy in 2024 and 2049 (using Average values).

Considering location specific values for estimating future, GWP $_{fossil}$ emissions from both systems shows that Malmö and Luleå presents lowest contributions in both current and future time, Stockholm and Umeå GWP $_{fossil}$ emission decrease drastically by future fossil free energy for both systems. See Figure 30.

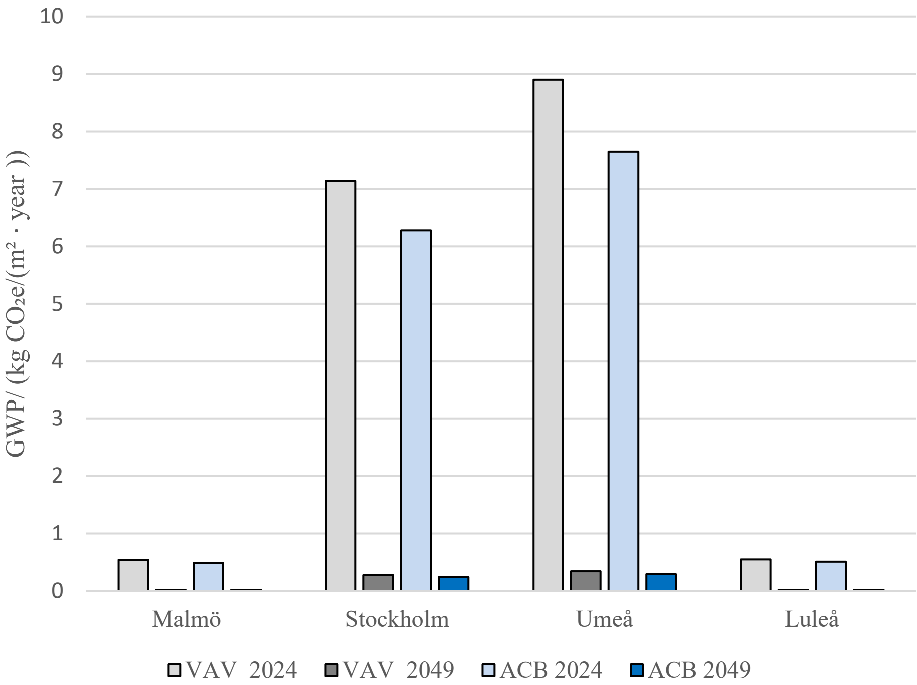

Figure 30: GWP fossil emitted by Operational energy in 2024 and 2049 (using location specific).

Comparing the results gained by average values and location specific values shows that average values for both system in Stockholm and Umeå results in significantly lower estimation. While in Malmö and Luleå the difference between results is insignificant and average values are higher than specific values for Malmö and Luleå. See Figure 31.

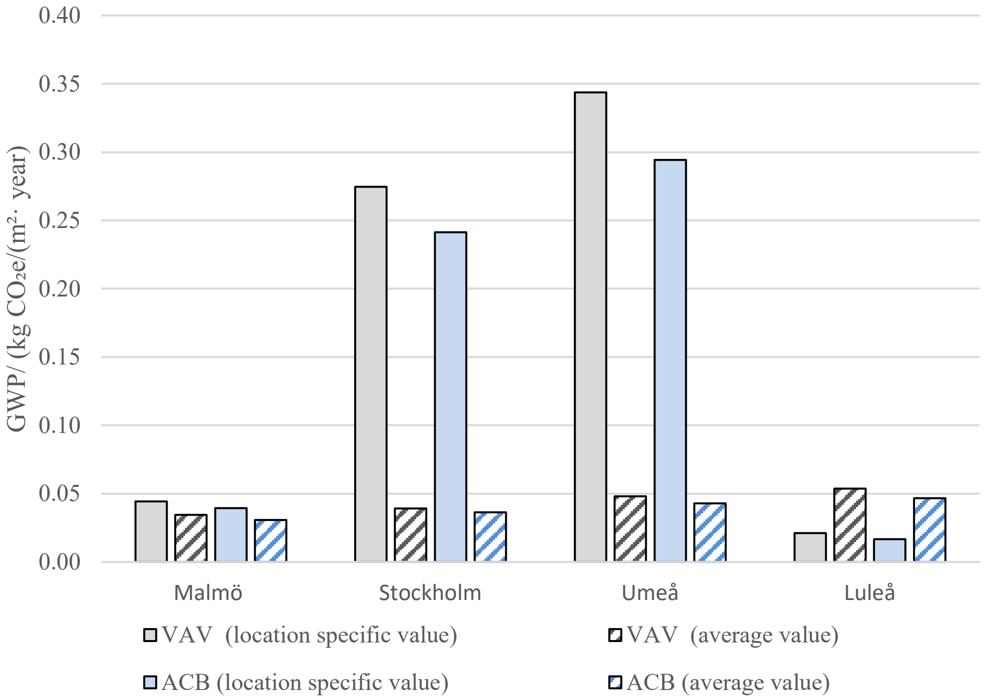

Figure 31: GWP $_{fossil}$ emitted by future energy in 2049 in both systems.

Considering the entire life cycle approach while considering future fossil free energy, Figure 32 shows that in VAV although operational GWP $_{fossil}$ is almost zero across different locations in 2049, the embodied GWP $_{fossil}$ from replacement of the systems still has impact. This can show the importance of acting to produce more environmentally friendly products.

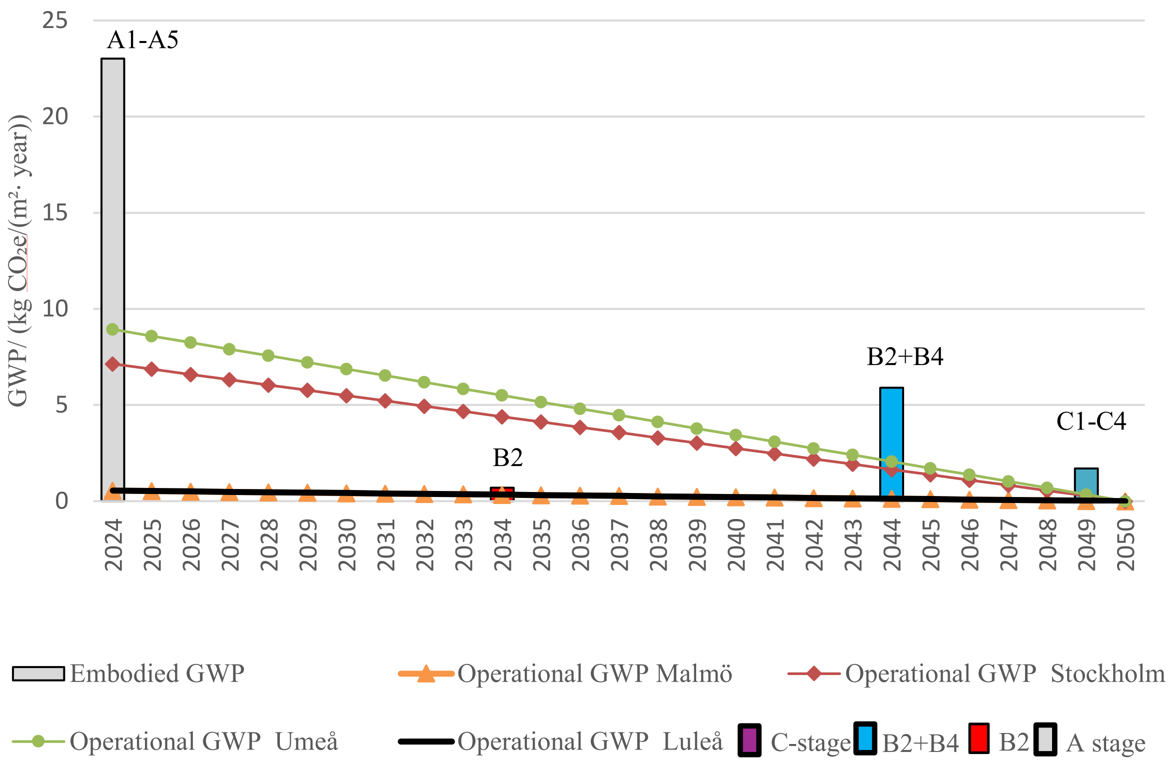

Figure 32: GWP-fossil over entire life cycle in VAV across different locations (by location specific values)

Regarding ACB, see Figures 33, as mentioned earlier the ACB has a lower GWP $_{fossil}$ emission over its entire life cycle across the different locations compared to VAV, but considering future energy target shows that embodied carbon from replacement still have a higher contribution compared to operational GWP $_{fossil}$ in 2049.

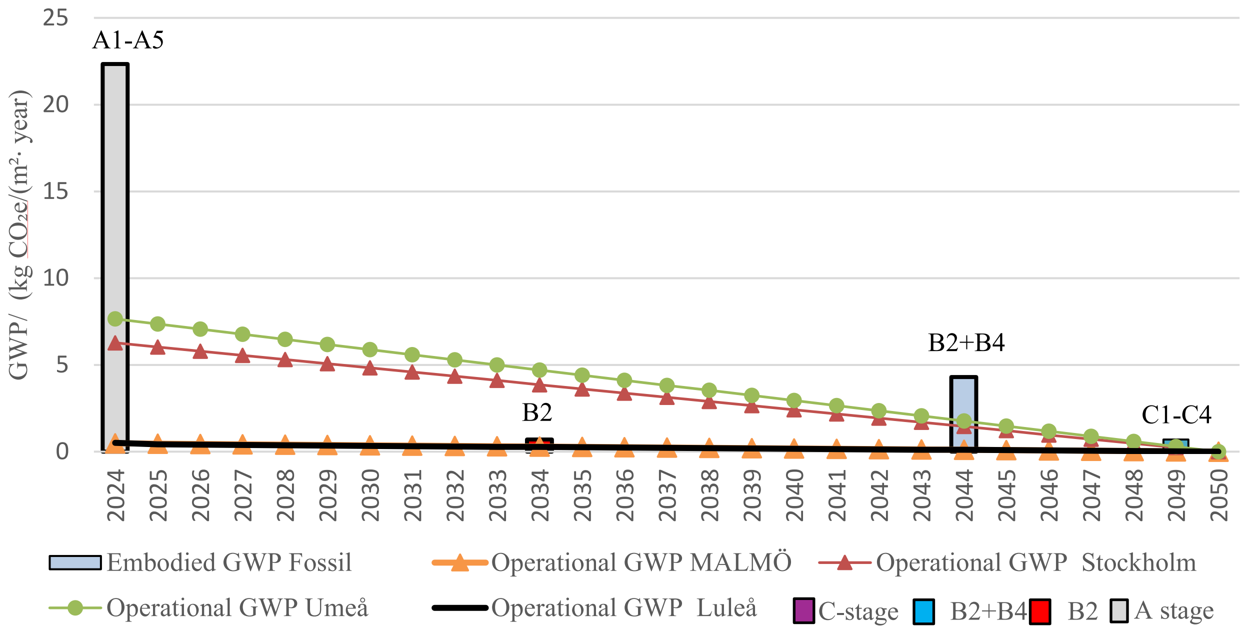

Figure 33: GWP $_{fossil}$ over entire life cycle in ACB across different locations (by location specific values)

5.4.3 Fan operation scenario

Figure 34 shows the results from different scenarios regarding fan operation, the results related to Malmö using average values by Böverket. In the base scenario it can be seen that ACB has emitted lower operational GWP $_{fossil}$, due to less time for fan operation time. On the other hand, considering a fair comparing between the systems' fan operation resulted in completely different outcomes. In the second scenario by turning off the fans during unoccupied time, VAV presents lower operational GWP $_{fossil}$ compared to ACB, in all the energy parameters including heating, cooling and fan energy use. This result is the same when both system's fan operate all the time.

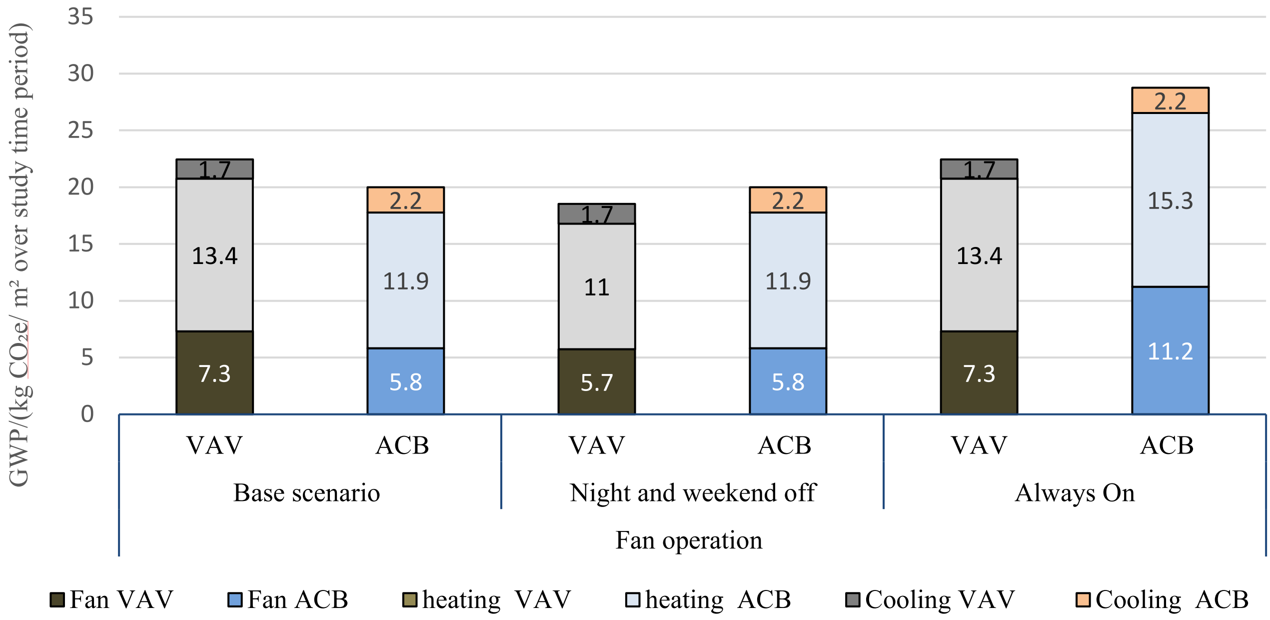

Figure 34: Operational GWP in different fan operation schedules.

Considering the entire life cycle approach with these scenarios, shows that VAV has a lower total GWP $_{fossil}$ only when two systems' fan operation all the time. See Figure 35.

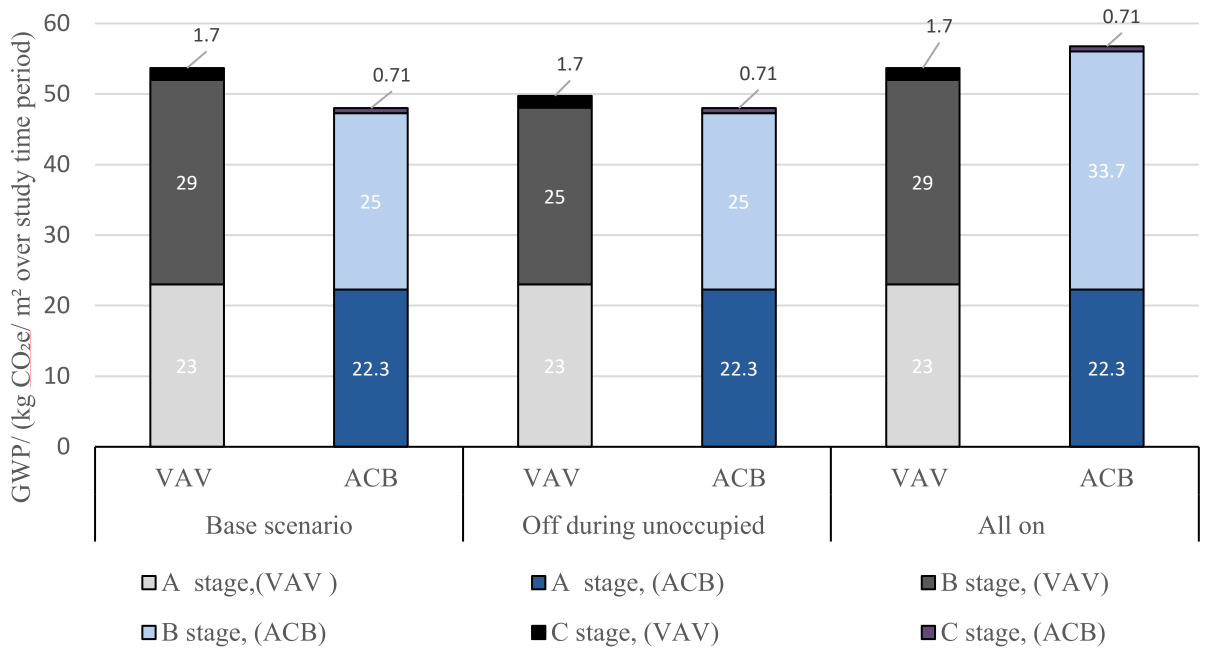

Figure 35: Entire LCA by considering different fan operational schedule in VAV and ACB

6 Discussion

This study was conducted to compare VAV and ACB systems in terms of their energy efficiency and GWP_{fossil} emissions in their entire life cycles. Three parametric studies were also done to assess the B6 module by changing locations and future energy target. In both parametric studies, two different databases for B6 including average values provided by Boverket and location specific values from providers were used, in order to compare the different between results by changing database.

Regarding energy use, in base scenario for fan operation, which presents a lower operation time for ACB compared to VAV, ACB is more energy efficient compared to VAV. Having a fan which is always on in VAV system and supplies minimum airflow during unoccupied hours, results in a higher fan energy use and accordingly more need for heating up the space, while it reduces the cooling demand in building. In contrast, in ACB, although the airflow is constant, fan energy use and need to heat up the space is less than the VAV, and it can be because of the fan operation time which is less than VAV. In ACB cooling demand is higher compared to VAV, while airflow is not supplied during unoccupied time in ACB, chilled water still circulates through pipes. In case of zero airflow, heat transfer between room air and water part remains. It can be because of the insufficient heat removal which makes chilled beams need more energy to cool the room air through water side.

Accordingly, in base scenario total operational GWP_{fossil} emitted by ACB is lower than VAV, due to the lower total energy consumption. The GWP_{fossil} emitted by energy used for fan and heating up the space is higher in VAV, as their energy consumption is higher than ACB. But the energy for cooling down the building is higher in ACB; therefore; GWP_{fossil} emissions from this energy parameter are higher in ACB.

Regarding embodied GWP_{fossil}, the highest emission of embodied GWP_{fossil} for both systems occur during stage A, 23,02 (kg Co_2 e /m^2) by VAV and 22,34 (kg Co_2 e /m^2) by ACB, while VAV system is emitting more GWP_{fossil} during A stage than ACB. The airflow in VAV is higher than ACB, accordingly, the weight and size of AHU and duct works is heavier, and GWP_{fossil} emitted from production and construction stage is also higher. Regarding replacement, GWP_{fossil} in VAV is higher, because replaced AHUs in VAV are heavier than replaced AHUs in ACB. Regarding B2, since the assumption was made, both systems have the same amount of emission during cleaning of the whole system equal to 0,9 kg Co_2 e /m^2. Regarding end-of-life stage, in both systems this stage has the lowest contribution compared to the other stages. The reason can be because of the dominant material in HVAC system which is steel, and it can be recycled instead of being landfill. VAV has a higher weight since the wasting process for VAV needs more energy compared to ACB, therefore, this energy emits more GWP_{fossil} in VAV.

Having an entire life cycle approach shows that the highest contribution of GWP_{fossil} emission in both systems come from use stage, because of summing up the emissions from B6, B4 and B2. In overall embodied GWP_{fossil} emission (by A stage, B4 and C stage) in both systems, is higher than operational GWP_{fossil}.

In respect of sensitivity analysis across different locations, since Sweden has cold climate, the energy that needs to heat up a building is higher than cooling energy. However, ACB system in all the location scenarios uses less energy compared to VAV in base scenario of fan operation schedule. By going northern Sweden locations, the heating energy use in building is increasing and this will increase the total energy use in both systems.

Considering different databases for B6 calculations while location is changing, resulting in different outcomes for different locations. In Malmö and Luleå, although the differences between B6 results, using average and location specific values are insignificant, by using average values as database the results become higher than using location specific values. On the other hand, for Stockholm and Umeå, by using specific values as database GWP_{fossil} emissions is almost 7 times higher than GWP_{fossil} using average values.

Comparing average values with specific values across different locations provides insights into the certainty of the results. Consistency across various locations and databases suggests greater reliability in the outcomes. However, significant differences between average and specific values in certain locations may indicate lower confidence in the results, highlighting the sensitivity of these areas to changes in input data. Comparing average values with specific values across different locations, shows that district heating average values has higher differences with location specific values, compared to electricity which has a lower discrepancy between average and location specific values across Sweden.

Considering future fossil free energy, shows that operational GWP $_{fossil}$ over the study service time, which is 25 years, becomes extremely low and almost equal in both systems across different locations. Moreover, considering different databases to estimate future GWP $_{fossil}$ emission from both systems also resulted in almost the same and low results. Therefore, the only concern in the future can be the manufacturing process and the GWP $_{fossil}$ emission through this process for both systems. Producing more environmentally friendly production can be a solution to reduce embodied GWP $_{fossil}$ from manufacturing and replacement stages.

Comparing B6 different database for future scenario, shows that these findings provide insights into the certainty of the results. Since the aim is to make the whole country district heating an electricity fossil free by 2050, both databases can result in reliable results while an insignificant difference still can be seen in some locations.

Regarding the last sensitivity analysis which focused on the times of fan operations, although on the base scenarios ACB can be considered as a more environmentally friendly alternative, in both operational and entire stages, considering two equal fan operation's schedules for both systems, including always on or off during unoccupied hours show that VAV have lower operational emission in an equal schedule compared to ACB. However, considering an entire LCA approach shows that VAV has a best option when both systems' fan is operating always.
In overall, although ACB presents consistently a lower embodied GWP $_{fossil}$ compared to VAV, the operational GWP can differ by changing the operation times of the fan in both systems, and only in base scenario ACB presents lower operational GWP $_{fossil}$. However, by considering the entire LCA, by changing operation schedule, results can be completely different compared to when only B6 was taken into consideration, this can show the importance of considering the entire LCA instead of only focus on some stages in life cycle.
Finally, one of the main limitations in this study was lack of data. Although the assumptions can be an approach, uncertainty of data shows that the more EPD is available the more accurate results are gained.

Finally, considering an entire life cycle can result in completely different outcomes, so it is better to consider entire LCA in calculations. Moreover, average values sometimes cannot be a good representative because they might result in overestimating or underestimating the real emissions, especially for district heating.

7 Conclusion

Which system is more energy efficient in terms of total energy use needed for fan, heating up and cooling down the case study building?

Results show that ACB system is more efficient than VAV system, in ACB primarily air is supplied by AHU while sensible cooling of room fulfills by chilled beams. Although cooling in ACB is more than VAV, in overall, ACB is a more energy efficient choice. Lower and constant air flow in ACB resulted in less fan energy and heating energy use, while since in VAV the airflow is higher and varied constantly and fan needs to operate more to provide fresh air.

Which system represents the lowest total GWP_{fossil}, considering the entire life cycle?

The ACB system shows a lower total GWP_{fossil} emission compared to VAV. Having lower primary supply air results in less weight in AHU and ducts systems. Therefore, embodied GWP_{fossil} in ACB is less than VAV. On the other hand, lower supply air resulted in lower operational energy use and accordingly lower Operational GWP_{fossil}.

Which system shows the lowest operational GWP_{fossil} results across different locations in Sweden?

Since Sweden is almost cold across the country while heating energy use is changing based on the weather, operational GWP_{fossil} increases in both system by going in northern Sweden, however, ACB contributes to a lower operational emission compared to VAV across the locations. Moreover, by changing B6 database ACB still shows lower operational GWP_{fossil}.

Which system represents the lowest operational GWP fossil in the future energy scenario?

Transition to future fossil-free energy sources significantly reduces the operational GWP_{fossil} emission, both systems will have a low emission in 2049. Using average values resulted in almost the same operational GWP_{fossil} emission while using location specific database, resulted in lower emission by ACB, specially in Malmö and Luleå compared to Stokholm and Umeå.

Which system shows the lowest GWP_{fossil} results in different fan operational schedules?

Using different schedules for fan operations shows that ACB cannot always be considered a better choice, especially in terms of entire LCA approach when its fan operates all the time without any off time it present higher GWP_{fossil} emission.

8 Future Works

For future investigation, a more comprehensive comparison is advised. For example, investigating the effect of transition to future fossil-free energy source manufacturing process of both systems (A stage), studying optimizations alternatives for each system both in design and manufacturing, comparing both systems in terms of entire life cycle costs, and investigating how recycled material can be optimized the HVAC manufacturing process.

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Appendix A

Table A: List of VAV dampers in the case study

Klass	Typ	Storlek	Serie	Produkt	Antal	L [m]	Isol [mm]	Ytarea [m2]	Tilluft
Flow damper VAV	VAV-spjäll	ø125	SP31	DCV-CF	56	l: endast 53 i l	870	Saknas	29
Flow damper VAV	VAV-spjäll	ø160	SP31	DCV-CF	36		240	3,3	8
Flow damper VAV	VAV-spjäll	ø200	SP31	DCV-CF	13		30	1,3	1
Flow damper VAV	VAV-spjäll	ø250	SP31	DCV-CF	14	15 i BOM	90	1,5	3
Flow damper VAV	VAV-spjäll	ø315	SP31	DCV-CF	1		30	0,1	1
Flow damper VAV	VAV-spjäll	ø400	SP31	DCV-CF	1		ingen	0,2	0
Flow damper VAV	VAV-spjäll	ø125	SP32	DCV-BL	2		Dimension saknas i	saknas	0
Flow damper VAV	VAV-spjäll	ø160	SP32	DCV-BL	4		ingen	0,5	0
Flow damper VAV	VAV-spjäll	ø200	SP32	DCV-BL	27		120	6	0
Flow damper VAV	VAV-spjäll	ø250	SP32	DCV-BL	14		60	2,8	1
Flow damper VAV	VAV-spjäll	ø315	SP32	DCV-BL	16		30	4,8	0
Flow damper VAV	VAV-spjäll	ø400	SP32	DCV-BL	3		ingen	1,6	0
Flow damper VAV	VAV-spjäll (mätfläns)	600x500	SP33	DCV-CF (JSPM)	5		150	2,5	5
Flow damper VAV	VAV-spjäll (mätfläns)	900X900	SP33	DCV-CF (JSPM)	1		30	0,8	1
Flow damper VAV	VAV-spjäll (mätfläns)	1000x300	SP33	DCV-CF (JSPM)	1		30	0,6	1
Flow damper VAV	VAV-spjäll (mätfläns)	1000x600	SP33	DCV-CF (JSPM)	12	DAST 12 I B(	360	8,4	12
Flow damper VAV	VAV-spjäll (mätfläns)	1200x500	SP33	DCV-CF (JSPM)	1		30	0,7	1
Flow damper VAV	VAV-spjäll (mätfläns)	1200x600	SP33	DCV-CF (JSPM)	2		60	1,6	2
Flow damper VAV	VAV-spjäll (mätfläns)	1400x700	SP33	DCV-CF (JSPM)	1		30	0,9	1
Flow damper VAV	VAV-spjäll (mätfläns)	500x300	SP34	DCV-BL (JSPM)	2		ingen	0,8	0
Flow damper VAV	VAV-spjäll (mätfläns)	600x300	SP34	DCV-BL (JSPM)	8		ingen	3,2	0
Flow damper VAV	VAV-spjäll (mätfläns)	600x400	SP34	DCV-BL (JSPM)	1		ingen	0,4	0
Flow damper VAV	VAV-spjäll (mätfläns)	700x300	SP34	DCV-BL (JSPM)	4		ingen	1,6	0
Flow damper VAV	VAV-spjäll (mätfläns)	700x400	SP34	DCV-BL (JSPM)	1		ingen	0,5	0
Flow damper VAV	VAV-spjäll (mätfläns)	700x500	SP34	DCV-BL (JSPM)	1		Dimensionen saknas i BOM		0
Flow damper VAV	VAV-spjäll (mätfläns)	800x200	SP34	DCV-BL (JSPM)	1		ingen	0,4	0
Flow damper VAV	VAV-spjäll (mätfläns)	800x300	SP34	DCV-BL (JSPM)	1		ingen	0,5	0
Flow damper VAV	VAV-spjäll (mätfläns)	800x400	SP34	DCV-BL (JSPM)	1		ingen	0,5	0
Flow damper VAV	VAV-spjäll (mätfläns)	900x200	SP34	DCV-BL (JSPM)	1		ingen	0,5	0
Flow damper VAV	VAV-spjäll (mätfläns)	1000x300	SP34	DCV-BL (JSPM)	1		ingen	0,6	0
Flow damper VAV	VAV-spjäll (mätfläns)	1000x400	SP34	DCV-BL (JSPM)	2		ingen	1,2	0
Flow damper VAV	VAV-spjäll	ø200	SP35	DCV-RC	3		90	0,6	3
Flow damper VAV	VAV-spjäll	ø315	SP35	DCV-RC	1		30	0,3	1
Flow damper VAV	VAV-spjäll	ø400	SP35	DCV-RC	1		30	0,4	1
Flow damper VAV	VAV-spjäll (mätfläns)	500x300	MF20	SMRD	2		ingen	0,8	0
Flow damper VAV	VAV-spjäll (mätfläns)	600x300	MF20	SMRD	8		ingen	3,2	0
Flow damper VAV	VAV-spjäll (mätfläns)	600x400	MF20	SMRD	1		ingen	0,4	0
Flow damper VAV	VAV-spjäll (mätfläns)	700x300	MF20	SMRD	4		ingen	1,6	0
Flow damper VAV	VAV-spjäll (mätfläns)	700x400	MF20	SMRD	1		ingen	0,5	0
Flow damper VAV	VAV-spjäll (mätfläns)	700x500	MF20	SMRD	1		Dimensionen saknas	Saknas	0
Flow damper VAV	VAV-spjäll (mätfläns)	800x200	MF20	SMRD	1			0,4	0
Flow damper VAV	VAV-spjäll (mätfläns)	800x300	MF20	SMRD	2			0,5	0
Flow damper VAV	VAV-spjäll (mätfläns)	800x400	MF20	SMRD	1		ingen	0,5	0
Flow damper VAV	VAV-spjäll (mätfläns)	900x200	MF20	SMRD	1			0,5	0
Flow damper VAV	VAV-spjäll (mätfläns)	1000x300	MF20	SMRD	1			0,6	0
Flow damper VAV	VAV-spjäll (mätfläns)	1000x400	MF20	SMRD	2		ingen	1,2	0

Appendix B

Table B: A stage and B stage calculation of VAV dampers

Massa deklarerad i EPD	A1-A3	Total A1-A3	A4	Total A4	Total CO2	Life time (year)	B4- Replace(25 years)
1,25155	14,9	1333,386601	0,169	15,1236467	1348,510247	20	1402,08
1,25155	14,9	1071,471375	0,169	12,1529304	1083,624306	20	1126,67
1,25155	14,9	464,3042627	0,169	5,26626983	469,5705325	20	488,23
1,25155	14,9	583,3566378	0,169	6,61659542	589,9732332	20	613,41
1,25155	14,9	65,47880628	0,169	0,74267908	66,22148536	20	68,85
1,25155	14,9	83,33666254	0,169	0,94522792	84,28189046	20	87,63
							0,00
							0,00
1,25155	14,9	47,62095002	0,169	0,54013024	48,16108026		50,07
1,25155	14,9	119,0523751	0,169	1,3503256	120,4027007	20	125,19
1,25155	14,9	964,3242379	0,169	10,9376373	975,2618753	20	1014,01
1,25155	14,9	583,3566378	0,169	6,61659542	589,9732332	20	613,41
1,25155	14,9	1047,6609	0,169	11,8828652	1059,543766	20	1101,64
1,25155	14,9	250,0099876	0,169	2,83568375	252,8456714	20	262,89
							0,00
							0,00
1	2,22	77,7	0,995	34,825	112,525	20	117,20
1	2,22	42,18	0,995	18,905	61,085	20	63,31
1	2,22	19,98	0,995	8,955	28,935	20	75,05
1	2,22	426,24	0,995	191,04	617,28	20	621,76
1	2,22	35,52	0,995	15,92	51,44	20	60,13
1	2,22	79,92	0,995	35,82	115,74	20	121,14
1	2,22	48,84	0,995	21,89	70,73	20	70,80
							0,00
							0,00
1	2,22	26,64	0,995	11,94	38,58	20	51,10
1	2,22	115,44	0,995	51,74	167,18	20	169,23
1	2,22	17,316	0,995	7,761	25,077	20	31,82
1	2,22	62,16	0,995	27,86	90,02	20	92,23
1	2,22	19,536	0,995	8,756	28,292	20	30,72
1	2,22	22,2	0,995	9,95	32,15	20	33,65
1	2,22	13,542	0,995	6,0695	19,6115	20	21,50
1	2,22	17,316	0,995	7,761	25,077	20	27,34
1	2,22	20,646	0,995	9,2535	29,8995	20	31,49
1	2,22	14,43	0,995	6,4675	20,8975	20	27,40
1	2,22	59,94	0,995	26,865	86,805	20	100,34
1	2,22	124,32	0,995	55,72	180,04	20	180,23
							0,00
							0,00
1,25155	14,9	110,7187088	0,169	1,2558028	111,9745116	20	116,42
1,25155	14,9	66,66933003	0,169	0,75618233	67,42551236	20	70,10
1,25155	14,9	84,52718629	0,169	0,95873117	85,48591746	20	88,88
							0,00
							0,00
1	2,22	16,428	0,995	7,363	23,791	20	31,50
1	2,22	71,04	0,995	31,84	102,88	20	104,07
1	2,22	9,99	0,995	4,4775	14,4675	20	18,51
1	2,22	37,296	0,995	16,716	54,012	20	55,27
1	2,22	11,1	0,995	4,975	16,075	20	17,41
1	2,22	12,21	0,995	5,4725	17,6825	20	18,61
1	2,22	8,436	0,995	3,781	12,217	20	14,39
1	2,22	19,98	0,995	8,955	28,935	20	30,21
1	2,22	11,544	0,995	5,174	16,718	20	17,70
1	2,22	8,88	0,995	3,98	12,86	20	16,23
1	2,22	31,08	0,995	13,93	45,01	20	52,26
1	2,22	66,6	0,995	29,85	96,45	20	96,55
		8 424			**9 196**		**9 629**

Appendix C

Table C: C stage of VAV dampers

C1	C2	C3	C4	C total	Databas
0	0,5091926	51,4437112	1,61975151	53,5726553	EPD-HUB - Dampers, *Klimaoprema RVP-C*
0	0,40917263	41,3386965	1,30158603	43,0494552	EPD-HUB - Dampers, *Klimaoprema RVP-C*
0	0,17730814	17,9134352	0,56402061	18,6547639	EPD-HUB - Dampers, *Klimaoprema RVP-C*
0	0,22277176	22,5066237	0,70864128	23,4380367	EPD-HUB - Dampers, *Klimaoprema RVP-C*
0	0,02500499	2,52625368	0,07954137	2,63080004	EPD-HUB - Dampers, *Klimaoprema RVP-C*
0	0,03182454	3,21523195	0,10123447	3,34829096	EPD-HUB - Dampers, *Klimaoprema RVP-C*
0	0,01818545	1,8372754	0,05784827	1,91330912	EPD-HUB - Dampers, *Klimaoprema RVP-C*
0	0,04546363	4,5931885	0,14462067	4,7832728	EPD-HUB - Dampers, *Klimaoprema RVP-C*
0	0,36825536	37,2048269	1,17142743	38,7445096	EPD-HUB - Dampers, *Klimaoprema RVP-C*
0	0,22277176	22,5066237	0,70864128	23,4380367	EPD-HUB - Dampers, *Klimaoprema RVP-C*
0	0,4000799	40,4200588	1,2726619	42,0928006	EPD-HUB - Dampers, *Klimaoprema RVP-C*
0	0,09547361	9,64569585	0,30370341	10,0448729	EPD-HUB - Dampers, *Klimaoprema RVP-C*
0					
0					
0	0,1169	1,938	2,622	4,6769	EPD-HUB - Dampers, *Lindinvent AB*
0	0,06346	0,918	1,242	2,22346	EPD-HUB - Dampers, *Lindinvent AB*
0	0,03006	19,584	26,496	46,11006	EPD-HUB - Dampers, *Lindinvent AB*
0	0,64128	1,632	2,208	4,48128	EPD-HUB - Dampers, *Lindinvent AB*
0	0,05344	3,672	4,968	8,69344	EPD-HUB - Dampers, *Lindinvent AB*
0	0,12024	2,244	3,036	5,40024	EPD-HUB - Dampers, *Lindinvent AB*
0	0,07348	0	0	0,07348	EPD-HUB - Dampers, *Lindinvent AB*
0	0,04008	5,304	7,176	12,52008	EPD-HUB - Dampers, *Lindinvent AB*
0	0,17368	0,7956	1,0764	2,04568	EPD-HUB - Dampers, *Lindinvent AB*
0	0,026052	2,856	3,864	6,746052	EPD-HUB - Dampers, *Lindinvent AB*
0	0,09352	0,8976	1,2144	2,20552	EPD-HUB - Dampers, *Lindinvent AB*
0	0,029392	1,02	1,38	2,429392	EPD-HUB - Dampers, *Lindinvent AB*
0	0,0334	0,6222	0,8418	1,4974	EPD-HUB - Dampers, *Lindinvent AB*
0	0,020374	0,7956	1,0764	1,892374	EPD-HUB - Dampers, *Lindinvent AB*
0	0,026052	0,9486	1,2834	2,258052	EPD-HUB - Dampers, *Lindinvent AB*
0	0,031062	0,663	0,897	1,591062	EPD-HUB - Dampers, *Lindinvent AB*
0	0,02171	2,754	3,726	6,50171	EPD-HUB - Dampers, *Lindinvent AB*
0	0,09018	5,712	7,728	13,53018	EPD-HUB - Dampers, *Lindinvent AB*
0	0,18704	0	0	0,18704	EPD-HUB - Dampers, *Lindinvent AB*
0	0,04228117	4,27166531	0,13449722	4,4484437	EPD-HUB - Dampers, *Klimaoprema RVP-C*
0	0,02545963	2,57218556	0,08098758	2,67863277	EPD-HUB - Dampers, *Klimaoprema RVP-C*
0	0,03227917	3,26116384	0,10268068	3,39612368	EPD-HUB - Dampers, *Klimaoprema RVP-C*
0					
0					
0	0,024716	3,264	4,416	7,704716	EPD-HUB - Dampers, *Lindinvent AB*
0	0,10688	0,459	0,621	1,18688	EPD-HUB - Dampers, *Lindinvent AB*
0	0,01503	1,7136	2,3184	4,04703	EPD-HUB - Dampers, *Lindinvent AB*
0	0,056112	0,51	0,69	1,256112	EPD-HUB - Dampers, *Lindinvent AB*
0	0,0167	0,561	0,759	1,3367	EPD-HUB - Dampers, *Lindinvent AB*
0	0,01837	0,3876	0,5244	0,93037	EPD-HUB - Dampers, *Lindinvent AB*
0	0,012692	0,918	1,242	2,172692	EPD-HUB - Dampers, *Lindinvent AB*
0	0,03006	0,5304	0,7176	1,27806	EPD-HUB - Dampers, *Lindinvent AB*
0	0,017368	0,408	0,552	0,977368	EPD-HUB - Dampers, *Lindinvent AB*
0	0,01336	1,428	1,932	3,37336	EPD-HUB - Dampers, *Lindinvent AB*
0	0,04676	3,06	4,14	7,24676	EPD-HUB - Dampers, *Lindinvent AB*
0	0,1002	0	0	0,1002	EPD-HUB - Dampers, *Lindinvent AB*
				432,907654	

Appendix D

Table D: Cleaning plan for air conditioning system, Source:(SS EN 15780:2011, 2011)

WORK	TARGET	ACTION
Exhaust air duct Cleaning	By removing dust, microbial particles the efficiency will be remained. Start by checking the end of duct in reused purposes.	1. Using vacuum cleaner or using a brushing or cleaning with compressed air in combination with air extraction equipment
Exhaust air terminal cleaning	In order to keep efficiency removing any dust, microbial contamination from these terminal units	1. If it is necessary, disassemble it 2. Cleaning by brush and vacuum 3. Clean with compressed air 4. Use any detergent/ if needed. 5. Rinse with water and dry in case of using wet approach. 6. Re-assemble it again
Cleaning of AHU	Removing dust	Use the AHU's cleaning regulations and methods.
Diffusers cleaning	Removing dust	1. Disassembly if needed n 2. Cleaning by brush and vacuum 3. Use compressed air. 4. Apply any Detergent if needed and vacuuming. 5. Rinse with water and dry if wet methods used. 6. Re-assembly the component again
Cleaning the Supply air duct	Removing dust, contamination to maintain efficiency. Start investigation from the beginning of the air duct if the system is to be re-used.	1. If existing openings such as access panels and other openings are insufficient, then install new access panels or removable sections of ductwork to permit cleaning. 2. Direct vacuum extraction or dislodging by means such as brushing or cleaning with compressed air in combination with air/dust extraction

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