Aalborg University, Denmark
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MSc thesis

Comparative Life Cycle Assessment of Tailor-Made Fabric, Glass Wool, and Galvanized Steel Ductwork for Ventilation Systems in a School and Office Building

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STUDENT REPORT

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Summary: This thesis presents a comparative life cycle assessment (LCA) of advanced alternatives to traditional steel ductwork for ventilation systems in Sofiendalskolen school and City Campus Aalborg. The research focuses on evaluating the global warming potential (GWP) of ductwork made from fabric, glass wool, and galvanized steel. To determine the environmental performance of the ductwork materials, key indicators such as embodied CO2 emissions calculated and analyzed in building and ventilation system level. The findings provided insights into the environmental impact of different ductwork materials and their contributions to CO2 emissions throughout the life cycle stages. At the ventilation system level, the air handling unit (AHU) has the highest contribution to the GWP, followed by other components. Fabric ductwork emerged as the most favorable option from an environmental perspective, despite the need for more frequent replacements. The findings suggested that fabric ductwork is a more sustainable alternative to steel ductwork, offering lower CO2 emissions and a smaller environmental footprint. On the other hand, glass wool ductwork was found to have higher CO2 emissions compared to steel ductwork scenarios. The need for frequent replacements of glass wool ductwork contributed to additional manufacturing processes, transportation, and associated emissions over time. Therefore, from an emissions perspective, glass wool ductwork may not be the most environmentally friendly choice for a ventilation system.

Preface

This thesis presents a comparative life cycle assessment (LCA) of advanced alternatives to traditional ductwork for ventilation systems in a Danish school and office building. The research focuses on evaluating the global warming potential (GWP) of ductwork made out of fabric and glass wool, in comparison to the conventional galvanized steel ductwork. This research aims to contribute to the knowledge and understanding of the environmental performance of ductwork materials, particularly in the context of Danish buildings.

This project conducted under the supervision of distinguished supervisors, Dr. Endrit Hoxha and Dr. Rasmus Lund Jensen, to whome I would like to extend my gratitude for their invaluable contributions and unwavering support throughout this research project. Furthermore, I extend my appreciation to the Department of Built Environment at Aalborg university, for providing me with the necessary resources and research facilities to carry out this study.

The subsequent chapters of this thesis outlines the detailed methodology employed in the design process of ventilation systems utilizing different duct types, present the results obtained from the design process, conduct a life cycle assessment (LCA) to evaluate the environmental performance of the ventilation systems, and provide a discussion of the findings. It is my hope that this thesis will serve as a valuable contribution to the field of sustainable building systems, offering insights and recommendations for stakeholders in the construction industry and policymakers to make informed decisions regarding the selection of ductwork materials that can effectively mitigate global warming potential.

Masoud Eris
Aalborg University
June 2023

Abstract:

This thesis presents a comprehensive comparative life cycle assessment (LCA) of advanced alternatives to traditional ductwork for ventilation systems in Danish commercial buildings. The research focuses on evaluating the global warming potential (GWP) of three ductwork materials including tailor-made fabric, glass wool, and galvanized Steel. Two case buildings, Sofiendalskolen school and City Campus Aalborg, were selected for the study. The methodology employed in this research involved a multi-step approach to analyze and design the ventilation systems in the case buildings. Subsequently, to conduct the life cycle assessment (LCA) of the ventilation systems, the LCAbyg tool was employed. The tool considered various stages of the life cycle, including production (A1-A3), replacements, operational energy use (B4 and B6), and end-of-life stages (C3 Waste processing, C4 Disposal). The "cradle-to-grave" approach was applied to assess the environmental impacts of the ventilation system and its components throughout their entire life cycle. The findings indicate that the choice of ductwork material significantly influences the environmental performance of ventilation systems. Fabric ductwork demonstrates a advantage over steel-based ductwork, showing lower CO_2 emissions and a smaller environmental footprint. Glass wool ductwork, however, leads to higher CO_2 emissions due to the need for frequent replacements. These findings have important implications for decision-making regarding ductwork material selection in commercial buildings, promoting sustainable practices and reducing environmental impact.

Keywords: comparative life cycle assessment, ventilation system, ductwork materials, fabric ductwork, glass wool ductwork, galvanized steel ductwork, commercial buildings.

Contents

1. Introduction

Upon the ratification of the Paris Agreement, the national climate act adopted by the Danish parliament, has made a firm commitment to reduce total greenhouse gas (GHG) emissions by 70% by the year 2030, as compared to the levels observed in 1990. Therefore, a long-term objective has been set to attain climate neutrality by the year 2050 (1). The building sector is responsible for 40% of worldwide energy consumption, 33% of greenhouse gas emissions, 30% of raw materials consumption, and 40% of solid waste productio (2). Under the voluntary sustainability standard introduced in 2020, buildings larger than 1000 m2 will be subject to a specific threshold limit of 12 kg CO2 eq./m2/year, while buildings smaller than 1000 m2 will only require a Life Cycle Assessment (LCA) calculation without any defined emission limits. However, the requirements concerning CO2 emissions in new constructions will progressively become more strict. By 2025, the threshold value will decrease to 10.5 kg CO2 eq./m2/year, followed by a reduction to 9 kg CO2 eq./m2/year in 2027, and finally reaching 7.5 kg CO2 eq./m2/year in 2029. These decreasing limits will be applicable to all buildings, regardless of their size (3). Given these facts, mitigation options for building emissions are particularly relevant in facilitating sustainable development and achieving stabilized GHG emissions and global mean temperature targets. Presently, the environmental impact regulations of the building sector within the EU have predominantly emphasized the operational stage, leading to the emergence of energy-efficient constructions. However, the embodied environmental impacts of building materials encompassing production, construction, maintenance, and disposal have emerged as a substantial contributor to global emissions. As a result, these impacts have become a significant fraction of the aggregated environmental impact of a building's lifecycle (4).

As indicated by a Danish report, the embodied impacts associated with materials are estimated to be roughly 2-4 times greater than the impacts arising from operations, both in a 50-year and an 80-year reference study period (5). The report highlights a distinct nessesities of directing the building and construction industry towards a reduced climate footprint, thereby facilitating sustainable development within society.

The EU legislations aimed to encourage HVAC manufacturers to integrate sustainability and efficiency into their systems. Consequently, the entire HVAC market is gradually transitioning towards more eco-friendly models. For intense, various studies have been undertaken to develop advanced designs that optimize energy usage, thermal, and environmental performance of HVAC systems. Renewable technologies such as solar, geothermal, and biomass heating and cooling systems are examples of alternatives that are being leveraged to improve the sustainability of HVAC systems(6) In fact, the incorporation of modified designs of different components and materials within HVAC systems, such as dampers, filters, humidifiers, dehumidifiers, heating and cooling coils, as well as ducts and fans, also could have a potential to significantly reduce the environmental impact (7).

During last decades, various industries have claimed that the utilization of fabric and glass wool ductwork products in the HVAC ductwork market represents an advancement compared to the conventional galvanized steel ductwork. However, the environmental impacts and life cycle assessment of these sustainable ductwork materials in comparison to traditional steel-based ducts have not been fully investigated. Therefore, it is essential to conduct a comparative life cycle assessment of these materials to determine their environmental impacts and overall sustainability performance in the context of ventilation systems for commercial buildings.

This research project aimed to assess the environmental impact of various types of ductwork, including traditional steel-based ductwork, tailor-made fabric ductwork, and glass wool-based ductwork, for use in Danish schools and office buildings. The selection of products was based on current market share and future potential market. Notably, this is the first study to compare the environmental impact of different types of ductwork materials in a danish school and office building context. The findings of this research can provide valuable insights to inform decision-making regarding the selection of materials for building ducting systems, promoting more sustainable building practices and reducing environmental impact.

1.1. Research questions

- How does the design process of ventilation systems differ when incorporating fabric ductwork, glass wool ductwork, and steel-based ductwork in Danish school and office buildings?
- What are the comparative environmental impacts of tailor-made fabric ductwork, and glass wool-based ductwork in comparison to traditional steel-based ductwork in Danish school and office buildings?
- Which ductwork material offers the most favorable environmental considerations for ventilation systems in terms of global warming potential (GWP) at the system level?

1.2. HVAC Ductworks Priciple and Fundamentals

Ducting is a vital component of HVAC systems, responsible for distributing conditioned air throughout the building. The basic principle of HVAC ducting is to deliver air from the air handling unit (AHU) to the occupied spaces in a building. The ductwork carries both supply and return air streams, which are essential for maintaining indoor air quality and ensuring occupant comfort (8)The design and construction of HVAC ductwork are based on certain fundamental principles. For example, the ductwork must be sized correctly to ensure the proper flow of air. The ductwork must be able to withstand the pressure and temperature differences that occur during operation. It must also be leak-free to prevent energy losses and minimize the infiltration of pollutants and contaminants from outside. Proper design of HVAC ductwork not only ensure the functionality of the system but also reduce embodied energy by saving the material consumption (8)In addition to proper sizing, ductwork must also be designed to minimize pressure losses and noise generation. This can be achieved through careful selection of duct materials and shapes, as well as the use of dampers, diffusers, and other components (9)

1.2.1 Ductwork clasification based on material

Ductwork can be made of various materials, such as galvanized Steel, carbon steel, aluminium, stainless steel and copper. The most common type of rigid air duct is constructed of galvanized steel or aluminum ducts (9)This has been claimed that, materials like fabric or glass wool ducts are an innovative alternative to traditional metal ductwork providing a more environmentally-friendly and energy-efficient solution. The choice of material depends on various factors, including cost, ease of installation, durability, and environmental impact (10)

1.2.2 Galvanized Steel ducts

The process of making galvanized ductwork involves various steps. Initially, the steel is cleaned and treated with acid, followed by galvanization with either zinc or polyester to create a protective layer that prevents corrosion and damage from environmental factors. The material is then leveled and trimmed before going through the interior and exterior welding stages. The duct is cut into the desired shape and size, welded together, and subjected to quality and strength testing before being shipped to customers. (11). Galvanized steel-based ductwork is a popular choice for ventilation systems due to its numerous advantages. Its high strength, rigidity, and durability make it a reliable option for long-lasting installations.

Additionally, galvanized steel's rust resistance and widespread availability ensure its suitability for various environments. The non-porous nature of the material enhances its workability and weldability, facilitating customization for specific requirements. Moreover, galvanized steel can handle high temperatures, making it suitable for applications involving heat. It also offers the flexibility to be insulated, enabling effective temperature control(11). However, there are some drawbacks to consider. Adapting galvanized steel ductwork to specific building heights or configurations can be challenging. Its weight can pose difficulties during transportation and installation, requiring extra effort and equipment. The material is susceptible to damage during the installation process(11). Proper maintenance is crucial to prevent corrosion, as the galvanized coating may wear off over time, exposing the underlying metal to potential rust. Furthermore, galvanized steel may not be the best choice for applications where weight is a concern. Despite these considerations, when properly maintained, galvanized steel ductwork has a commendable service life. The service life of galvanized ducting systems is highly dependent on the conditions of use and contingent on the specific additives and other compounds integrated into the material. However, the average lifespan under normal conditions is a minimum of 50 years (12)

1.2.3 Fabric ductwork

Tailor-made fabric ductwork is typically manufactured using a process called computer-aided design and manufacturing (CAD/CAM). According to Prihoda (https://www.prihoda.com/en/), this process involves using specialized software to design the ductwork, which is then fed into a computer-controlled cutting machine that precisely cuts the fabric to the desired shape and size. The cut pieces are then sewn together using high-strength threads, and the finished ductwork is fitted with suspension hardware and air distribution nozzles.

Fabric ducting is commonly made from a flexible and fire-resistant material, including neoprene-coated or PVC-coated polyester. These materials help reduce energy loss and negate the need for additional coatings to improve the duct's conductivity(11). In addition to conventional materials, recycled PET bottles can also be used in the production of fabric ducts.

Figure 1:Prihoda designed fabric ducting in an office environment. (https://www.prihoda.com/en/)

The manufacturing process involves melting plastic bottles and extruding them into a fiber-like material that is then woven into a polyester fabric. This approach provides a sustainable alternative to traditional materials for ductwork production (https://www.prihoda.com/en/). Figure 1 shows office ventilation system where Prihoda tailor-made fabric ducting and diffusers has been used to distribute air to desired locations.

1.2.4 Fabric diffusers

Air distribution through fabric diffusers can be achieved using various options, including permeable fabric, microperforation, perforation, small and large nozzles, adapters, and second end (figure2A). The permeable fabric option allows air to diffuse through a permeable surface of the fabric to achieve uniform airflow distribution (figure 2A. A) . Microperforation is obtained by creating small holes measuring between 200 and 400 µm on the fabric (figure 2A. B). Perforation, on the other hand, involves creating larger holes with a diameter greater than 5/32" (4mm) on the fabric to allow air to diffuse (figure 2A. C). The small nozzle option directs air through a small opening, while the large nozzle option uses a larger opening to diffuse the air (figure 2A. D and E). An adapter can be used to guide the air off into another ducting branch, whether fabric or metal, while the second end option involves leading the air to another diffuser or ducting, such as back to a metal duct.

The airflow models for fabric ducting and diffusers offer numerous combinations and solutions to meet the specific air distribution requirements of different projects (figure 2B). The choice of airflow model depends on factors such as velocity, throw, and heating or cooling needs. Microperforation is suitable for low-velocity and laminar air dispersion, making it ideal for applications where a gentle air throw is desired. While, perforation is capable of producing a low to medium air throw, making it suitable for heating, cooling, and ventilating applications. For situations that require high-velocity or spot cooling/heating, the nozzle airflow model is employed. Nozzles with a diameter of 3-4" and above offer very long throws and can deliver air at a high velocity, enabling effective spot cooling or heating (figure 2B).

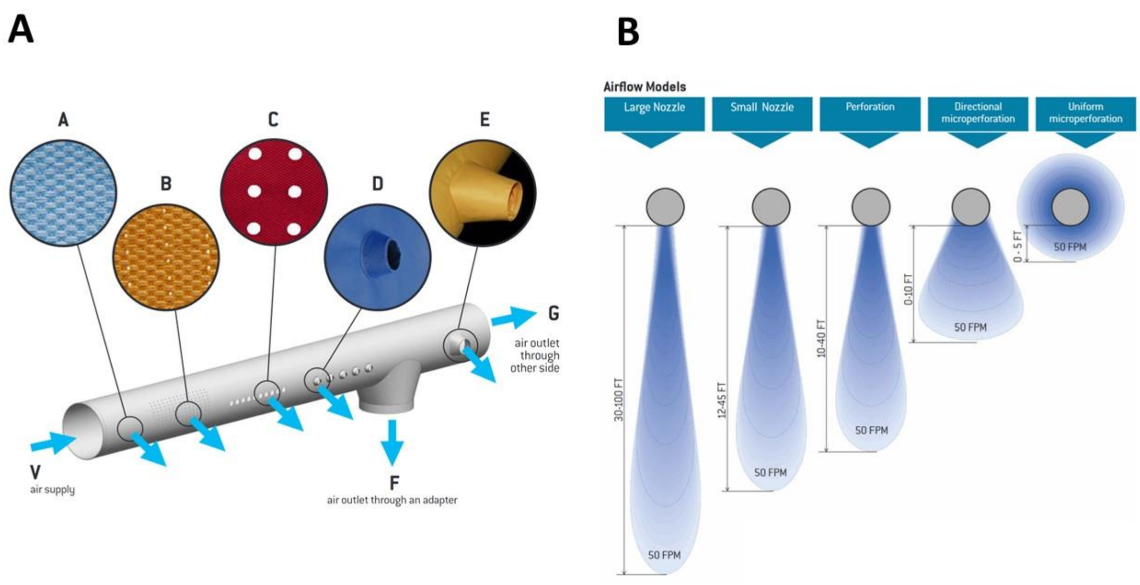

Figure 2:Air distribution options (A) and airflow models for Prihoda fabric ducting and diffusers (B).

1.2.5 Air inlets for negative pressure ducting

Ducting made from impermeable fabric or insulated ducting transports air to the destination without diffusion. Negative pressure ducting is only supplied in square or triangular cross-section.
To prevent collapse under negative pressure and maintain flexibility, the duct walls need to be stretched and held taut both lengthwise and crosswise. This is achieved through the use of track profiles, threaded rods, and weighted rods for triangular cross-sections (figure 3). Air enters the duct through perforations that can be placed on any side and at any point along its length. To ensure balanced extraction and exhaust rates, perforation diameters or spacing can be adjusted progressively along the duct.
Negative pressure fabric ducting is designed for applications requiring regular and thorough cleaning, such as the food industry. It is also suitable for corrosive environments like pools and natatorium return ducts. If made from Prihoda NMI material like Polyethersulfone, the ducting will have antibacterial properties(13).

Figure 3:Negative pressure ducting with a stretching feature.

1.2.6 Advantages and disadvantages of using fabric ductwork

The utilization of air-permeable materials helps prevent water condensation. Polyester fabric ducts offer an innovative alternative to traditional metal ductwork that typically relies on grilles and diffusers for air distribution. Instead, the fabric duct features perforations along its length that enable it to provide uniform and draft-free air distribution at a low velocity which travels thuogh great distance (13)
According to a study conducted by Fontanini et al, fabric ducting systems demonstrate better thermal efficiency and performance compared to conventional sheet-metal ductwork.
The research indicated that fabric ducting systems were able to heat the room more quickly and evenly than traditional ductwork (14)Fabric ductwork offers several advantages in certain applications, but it also has its fair share of disadvantages. One of the significant advantages of fabric ducts is their lightweight nature compared to metal ducts. This characteristic makes them easier to install, maintain, and modify, reducing labor and time requirements. Additionally, fabric ducts can be designed in various shapes, sizes, and colors, allowing them to blend seamlessly with the interior decor of a building, providing aesthetic appeal.
Cost-effectiveness is another advantage of fabric ducts, especially for large commercial or industrial spaces. They are often cheaper to purchase, install, and maintain compared to their metal counterparts, leading to cost savings without compromising functionality. However, fabric ducts come with some drawbacks to consider. Their durability may be lower than that of metal ducts, particularly in high-traffic areas or harsh environmental conditions. As a result, fabric ducts may require more frequent replacement or repair.
Cleaning fabric ducts can also be challenging and may necessitate specialized equipment or expertise, especially when contaminated with dust, debris, or other pollutants. Another disadvantage of fabric ducts is their susceptibility to damage from punctures, tears, or abrasions, especially in areas with high foot traffic or exposure to sharp objects or moving equipment. Lastly, fabric ducts may not be suitable for extreme temperature conditions. In areas where the temperature can exceed 200 degrees Fahrenheit or fall below freezing, fabric ducts may not provide the necessary thermal insulation or structural integrity. The service-life of this product is about 25 years including a maximum of 25 wash cycles of the product as part of maintenance (https://www.prihoda.com/en/).

1.2.7 Glass wool ductworks

As an example of glass wool ductworks, the Climate Recovery (CR) ducts are a pre-insulated ductwork system designed for HVAC applications https://climaterecovery.pl/en/. According to the information provided by the manufacture, CR ducts are comprised of glass wool (87%), binding agent (6%), aluminum foil (2.7%), polyethylene foil (2.6%), PET (1.4%), and other miscellaneous materials (0.3%). It is notable that the production of each unit of this product employs 1.52 kilograms of secondary materials derived from recycled glass, such as bottles and smashed car windows. The glass fibers are bound together with the addition of sand and baking soda, and then subjected to heating, spinning, and pressure molding processes to form mineral insulation wool, which is subsequently heated to the desired shape.

Glass wool-based ductwork in ventilation systems is shown to have superior thermal and acoustic insulation properties (figure 1). A study by Lippmann aimed to evaluate the thermal insulation and acoustic properties of glass wool in the context of compliance with the Energy Conservation Building Code (ECBC) and its potential as a green building material. The study also suggests that wool-based materials in the building components can effectively reduce thermal conductivity while also meeting the requirements for energy efficiency and sustainability.

Glass wool-based materials also have a higher sound absorption coefficient than other common insulation materials, such as rock wool and foam insulation. This means that glass wool ducts can effectively reduce noise levels in buildings, improving indoor acoustic comfort. This enables them to effectively reduce unwanted noise levels and eliminate the need for duct silencers. Also, their lightweight construction and standardized dimensions allow for easy handling and installation, facilitating retrofit and adaptation to existing ventilation systems (15)

However, one of the disadvantages of using glass wool-based ductworks is the potential health risks associated with the fibers. Exposure to glass wool fibers can cause respiratory and skin irritation and may increase the risk of lung cancer. Therefore, safety precautions should be taken when handling and installing glass wool materials to minimize the risk of exposure to fibers (15).

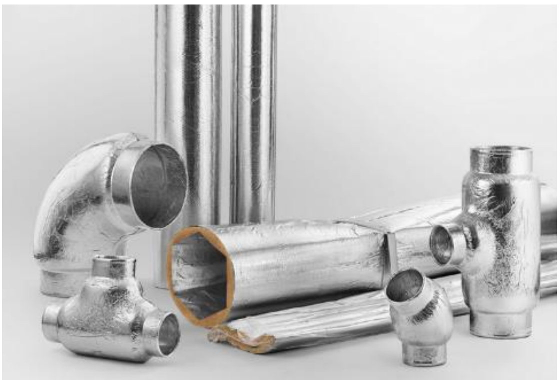

Figure 4:Climate Recovery (CR)glass-wool based ductworks

1.2.8 Service Life

According to the information provided by Climate Recovery (CR) https://climaterecovery.pl/en/ the service life of the ducts, which are a type of pre-insulated ductwork system made with glass wool insulation, is estimated to be around 30 years. This estimate is based on the manufacturer's specifications and testing of the product under certain conditions. It's worth noting that the actual service life of any ductwork system can be affected by various factors, including but not limited to environmental conditions, humidity, temperature, maintenance practices, and material degradation over time.

Each material used in building construction possesses unique characteristics that may make it well-suited for specific applications. However, it's important to recognize that the entire life cycle of a material, from its production to disposal, can contribute to environmental pressures that affect our planet. Therefore, evaluating a material's environmental impact through a life cycle assessment (LCA) is essential to make informed decisions regarding material selection for building projects. LCA offers a holistic approach to analyzing the potential environmental impacts of a material throughout its life cycle. In the next chapters, we will provide a detailed methodology for the process of designing ventilation systems and life cycle assessment using different duct types.

2. Methodology:

2.1. Goals and scope:

This study aimed to conduct a comparative life cycle assessment (LCA) of advanced alternatives to traditional ductwork for ventilation systems in two commercial case buildings individually. Specifically, the research focused on evaluating the global warming potential (GWP) of ductwork made from fabric and glass wool, in comparison to the conventional galvanized steel ductwork. The selection of duct material was based on current market share and future potential market. The focus of the investigation was solely on the ventilation system and its components within the building. Other HVAC systems, specifically heating systems, and their associated components were not taken into account in the assessment. The inventory for analysis included only the ventilation components that were designed in the 3D ventilation models. Components related to the electrical model and fire safety were excluded from consideration. Furthermore, due to insufficient information, the calculations did not incorporate the heating/cooling sytems running through the operational components.

2.2. The case building description

A. **Danish school building:** Sofiendalskolen is a primary and lower secondary school with several small building complexes, located in a residential neighborhood at Lange Müllers vej 18, 9200 Aalborg, as shown in figure 5A. The building, constructed in 1970, consists of brick structural walls and roofing felt for the roof. It has 38 classes that can accommodate approximately 650 students. A significant refurbishment and extension took place in 2006-2007 to provide flexible learning environments. For this study, a specific area of 1618 m2 was selected, consisting of classrooms, a teacher's office, prep-rooms for teachers, and a storage room. This decision was driven by the unavailability of data pertaining to other sections within the building.

B. **The City Campus Aalborg in Denmark**: The City Campus (figure 5B) was constructed in 2012-2013, covers a gross floor area of 20,000 m2 and was built for Aalborg Kommune. The building, which is organized around a large atrium and a south-facing outdoor courtyard. The courtyardis visible from the surrounding environment through several large windows. The public atrium houses exhibition areas, cafeteria, and an auditorium. City Campus Aalborg accommodates 900 students and permanent staff and researchers.

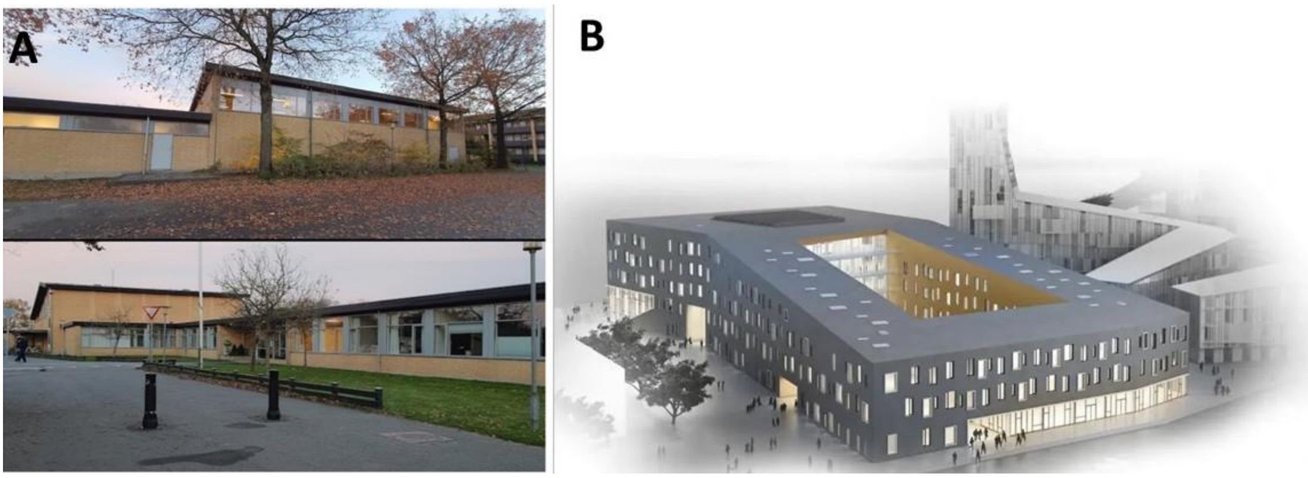

Figure 5:view of the case buildings. Sofiendalskolen school building (A). The City Campus Aalborg in Denmark (B).

2.3. Variable Air Volume (VAV) system and zoning

In the context of designing a ventilation system for the case buildings, the implementation of a Variable Air Volume (VAV) system has been deemed as an efficient solution. The VAV system utilizes flow control to effectively condition each building zone while simultaneously adhering to the minimum flow rate requirements resulting in energy savings, and reduced operating costs as detailed by (16)

As an important consideration when designing a ventilation system for the buildings, zoning has been performed based on demand profiles (Appendix 1) to ensure optimal comfort levels within each zone. Zoning involved dividing the building into separate areas based on various factors such as exposure to exterior walls and windows, orientation to the sun, equipment and people loading, activities, and ventilation requirements, as specified by the Building Regulations 2018, have been taken into consideration while determining the demand profile. The positioning of ducts has been determined by zoning requirements, which has necessitated the installation of multiple ducts to provide air for each specific area (figure 6 and 7).

As per the Building Regulations 2018, it is mandatory to ensure a minimum supply air and outdoor exhaust air of at least 3.0 l/s per child and 5.0 l/s per adult, along with 0.35 l/s per m2 heated floor area in day care institutions. Additionally, it is necessary to ensure that the maximum CO2 concentration in indoor air does not exceed 1.000 PPM for dimensioning conditions in teaching rooms and other similar areas (Appendix 1).

Upon identifying the specific zones within the buildings, a preliminary layout of the ductwork has been drafted. Figure 6 shows the zoning layout for school building, where orange regions have been designated to possess different ranges of interior loads, thereby necessitating distinct parameters for supply air to be implemented in the VAV HVAC system. Grey highlighted areas signify high-traffic corridors and open spaces, where natural ventilation has been deemed suitable, without the implementation of any mechanical ventilation.

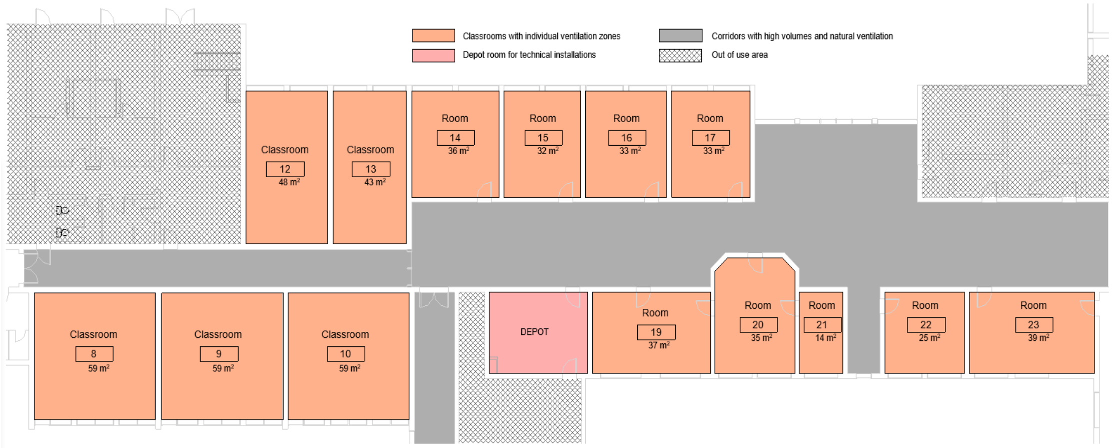

Figure 6:Zoning layout of Sofiendalskolen school building.

In the case study of the Campus Aalborg building (figure 7), the building's zoning requirements have also been carefully analyzed to ensure appropriate ventilation is provided to specific areas. The study area (green), meeting rooms (yellow), office area (orange) has also been identified as a high-priority zone that necessitates a ventilation system to enhance occupant comfort. Additionally, the pink corridors have been found to only require ventilation in certain areas, while the corridors highlighted by grey color and closed space installation room (dark green), does not require any ventilation system.

Figure 7:Zoning layout of the City Campus Aalborg building.

2.4. Estimation of required air change rate (ACR) and volume flow for each zone.

To ensure that the ventilation system is operating effectively, the maximum required volume flow for each room determined by evaluating the number of occupants, the CO2 concentration levels in each zone, and BR18's minimum requirements, taking into consideration that the CO2 concentration should not exceed 1000 PPM. The formula for estimating the air change rate (ACR) and volume flow for each zone of a building is as follows:

$c = (c_0 - c_i) \cdot e^{-nt} + c_I$ where,

$c_0 = CO_2$ concentration in the room at start $[m^3/m^3]$

$c_i = CO_2$ concentration in the inlet air

$e =$ the constant 2.718

$n =$ number of air shifts per h $[1/h]$

$t =$ time constant

Therefore, the air flow is calculated as follows:

$q_v = \frac{q_{co2}}{c_{co2\max} - c_i}$ where,

$q_{co2} =$ CO2 emission from a person at 1.2MET, Adult $= \frac{0.0052L}{s}$, Child $= \frac{0.0029L}{s}$

$c_{CO2maxi} =$ maximum allowed CO2 concentration $= 1000PP$

$c_i =$ CO2 concentration in the supply air $= 400$ PPM

The detailed results of the estimation of required air change rate (ACH) and volume flow for each zone are presented in Appendix 1 of this report.

2.5. Designing of ventilation systems by applying galvanized steel ductwork

The Lindab CADvent 7, which is plugin tool on AutoCAD, version 2020 was employed for drafting, dimensioning, designing, and products selecting to design the ventilation system (figure 8 and 9). Comprehensive evaluations of the air distribution in the rooms were analysed using LindQST (https://www.lindab.com/support/software-ventilation-system/lindqst/) and presented in Appendix 2. The goal was to analyze and visualize how selected diffusers and their arrangement affects the indoor environment of the rooms in terms of air distribution, acoustics, and throw length. The selection of diffusers was based on the needed airflow rate, room space type and ventilation service type (Appendix 3). Afterward, the tool performed various calculations, including pressure drop, duct sizing, balancing calculations (Appendix 4), acoustic (Appendix 5) and list of components based on local standards (Appendix 6).

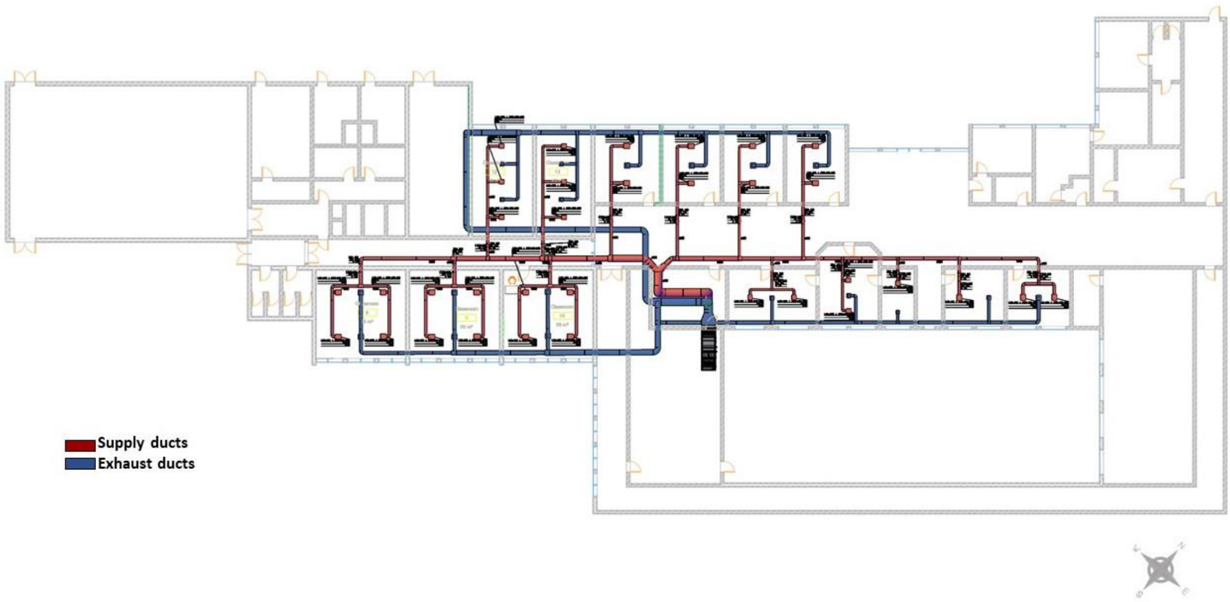

Figure 8:Ventilation layout in school building applying galvanized steel ductwork.

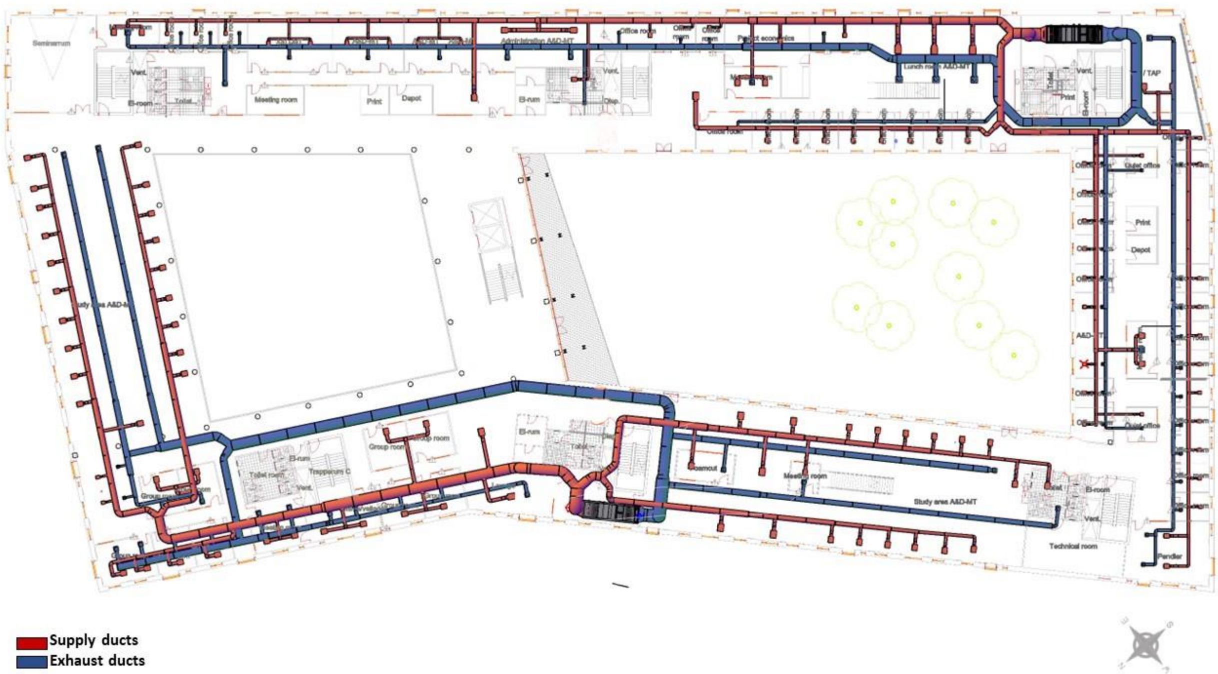

Figure 9:Ventilation layout in City Campus Aalborg building applying galvanized steel ductwork.

2.6. Designing the ventilation systems by applying fabric ductwork.

In this case, we utilized fabric ductwork products provided by Prihoda (https://www.prihoda.com/en/) to address the requirements for well-engineered ventilation system. By selecting Prihoda's product, we ensured the incorporation of a widely recognized ducting material in our analysis. Initially, the preliminary layout of the ventilation system was created using Lindab CADvent 7 software. Once the layout was finalized, we proceeded to import it into the Prihoda Air Tailor design software (https://www.prihoda.com/en/), a specialized tool offered the manufacture. The software facilitated the determination of various critical factors, including duct sizes, pressure losses, airflow speed, velocity, and noise levels. These parameters are essential for optimizing the performance and functionality of the fabric ductwork distribution elements. All the pertinent findings and calculations were collected and summarized in Appendix 4. The ventilation system's design is illustrated in the resulting 2-D view (shown in figure 10 and 11). For a comprehensive list of components, see Appendix 6.

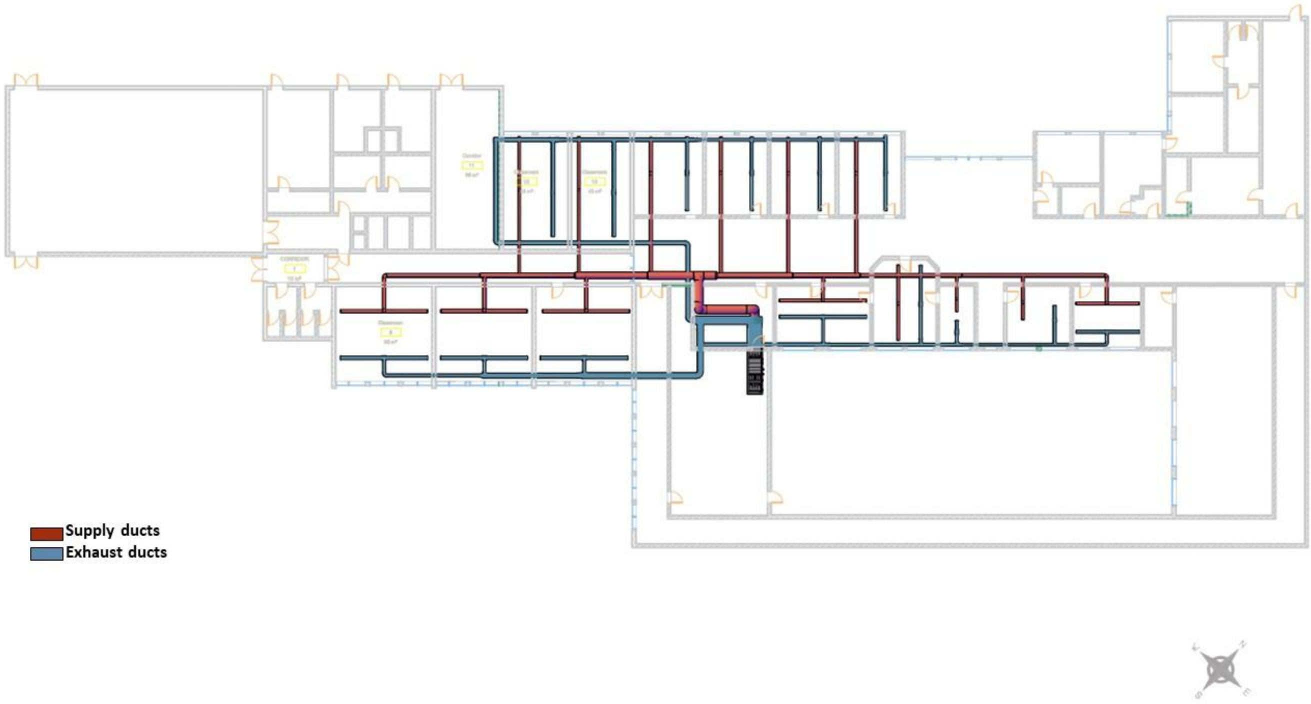

Figure 10:Ventilation layout for the school building applying Prihoda tailor made fabric ductwork.

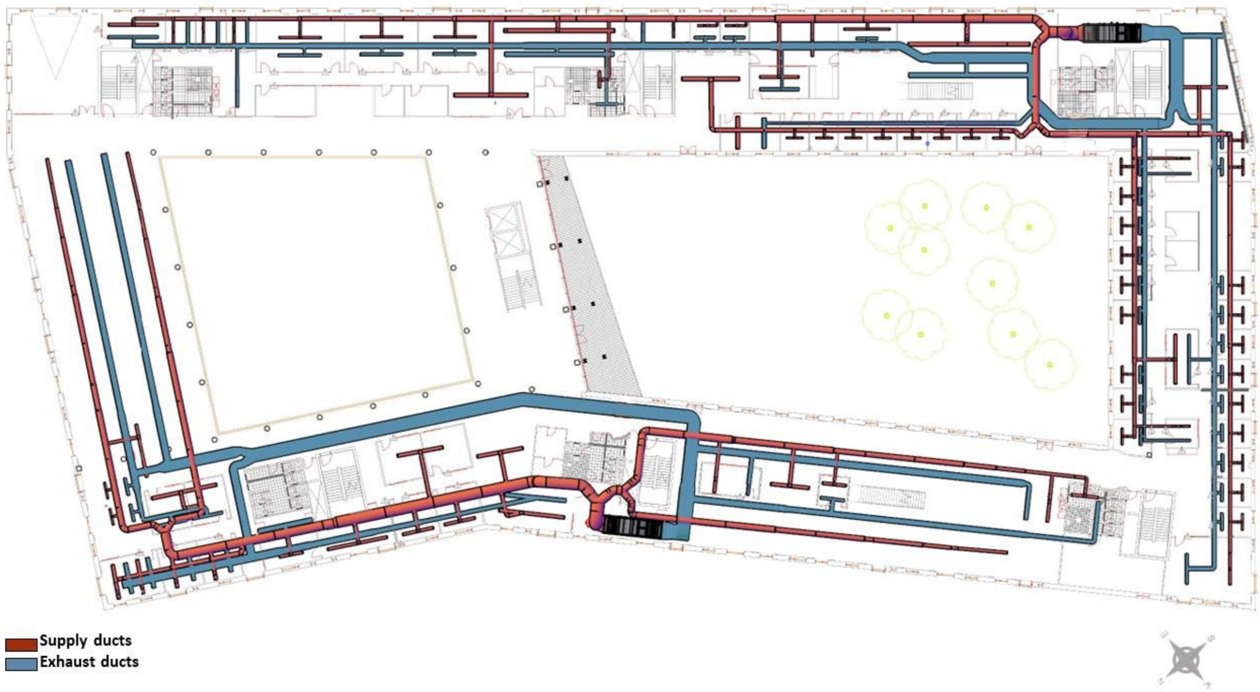

Figure 11:Ventilation layout for City Campus Aalborg building applying Prihoda tailor made fabric ductwork.

2.7. Designing the ventilation systems by applying glass wool ductwork.

Climate Recovery (CR) duct (https://www.climaterecovery.com/) was chosen as the preferred duct component due to its glass-wool composition and its tailored design for HVAC applications. To design the ventilation system using CR ducts, Lindab CADvent 7 was employed to create a detailed layout of the system, incorporating the specific requirements and constraints of the project. However, the use of CR ducts for a ventilation system design was limited due to the maximum diameter of 315mm for glass wool-based ductwork. To overcome this challenge, a mixture of steel-based and glass wool ductwork was employed to attain the necessary airflow rates and duct sizes in the case buildings. The design of the ventilation system is shown in the generated 2-D view, as presented in Figure 12. The results collected from calculations including air volume flow, duct sizing, velocity, pressure loss for each component is presented in Appendix 4. To find a comprehensive list of components, refer to Appendix 6.

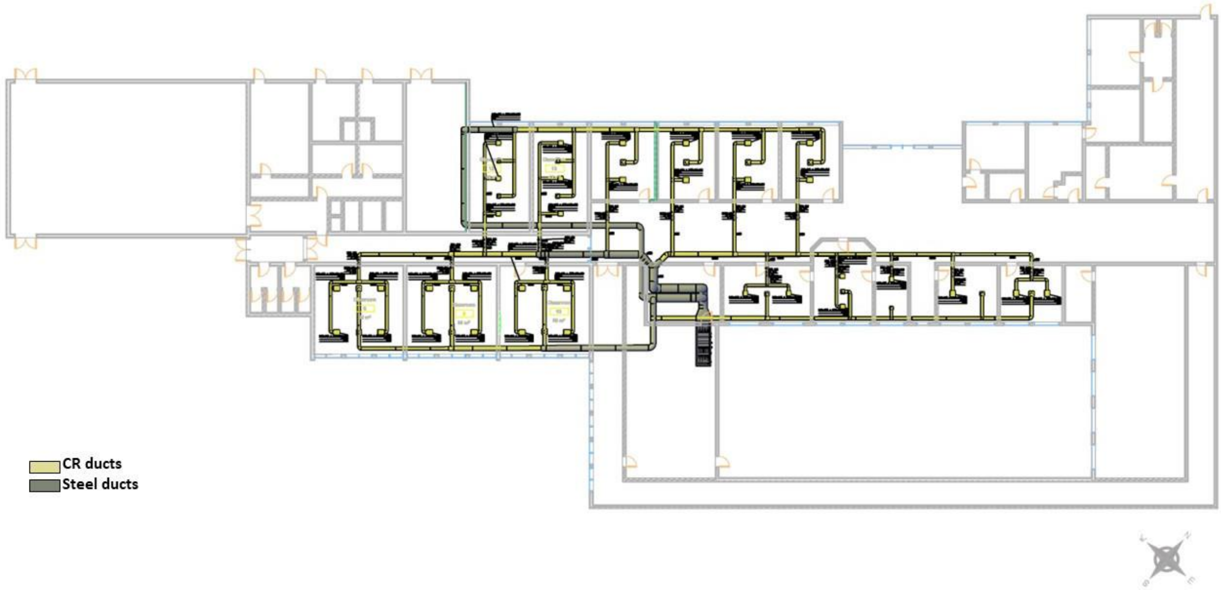

Figure 12: Ventilation layout in school building applying Climate Recovery ductwork.

Figure 13:Ventilation system layout in City Campus Aalborg building applying Climate Recovery ductwork.

2.8. Determination of air handling unit (AHU)

Following an analysis of the total pressure loss and maximum required air flow for the respective case buildings, a ventilation unit with plate heat recovery was chosen utilizing the SystemAirCAD program (available at https://www.systemair.com/gb/). The program suggested an air handling unit along with its respective components. However, certain modifications had to be made to ensure that each component met the specific requirements for its intended function. The modifications were made to meet the specific requirements for each component, including the filter standard (ISO16890), heat recovery efficiency (DS 447), and specific fan power (SFP) regulations (DS 447). This process ensures that the selected ventilation unit with plate heat recovery functions effectively and efficiently for the respective case buildings. Consequently, for the school building scenario, the GENIOX-11 air handling unit was selected, while the City Campus building required two AHUs, specifically the GENIOX-20H and GENIOX-24 models. It is noteworthy that all AHUs provided are manufactured by Systemair. The characteristics of AHU components are presented in Appendix 7.

2.9. Life cycle assessment (LCA) analysis

The case buildings underwent a life cycle assessment (LCA) to analyse the Global Warming Potential (GWP), caused by the ventilation system and its various components in the case buildings. The study focused on the embodied carbon of the ventilation systems which translates into the environmental impact category of GWP measured in [kg CO2 eq.]. The remaining impact category indicators were excluded from the study.

The investigation only considered the ventilation system and its components in the buildings (present in the 3D ventilation models), excluding other HVAC systems like heating and cooling. The BIM model and the project documentation for each case- building has been used for quantifying the building components and to define the building material type, size, thickness, and other building properties.

To conduct the Life Cycle Assessment in City Campus Aalborg, our focus was directed towards a single floor of the building. By concentrating on this specific floor, we aimed to streamline the assessment process and ensure a manageable scope for data collection and analysis. Subsequently, the results obtained from the LCA analysis were multiplied by the number of floors in the building. This approach enabled us to simplify the assessment by extending the findings to cover the entire building.

The LCAbyg tool (English version 6.2.0 (BR18, 2023)) developed by the Danish Building Research Institute and (Energy and Building in 2014) were employed to run the analysis. This tool is compliant with the EN 15978:2012 standard and covers various stages such as product (A1-A3), replacements, operational energy use (B4 and B6), and end-of-life stages (C3 Waste processing, C4 Disposal)(17).

The LCAbyg tool was populated with general information regarding the case buildings, including a concise description of the buildings, addresses, building type, area, year of commissioning, and reference study period (RSP). The analysis primarily relied on materials that were available within the LCAbyg tool. The building components were either selected from the construction catalogue within the tool or were newly defined using Environmental Product Declarations (EPDs) of the specific products provided by contractors and building declarations containing information about product content and production energy. The reference study period for the assessment defined as 50 years as recommended by the Danish agency for housing and planning per Voluntary Sustainability Class calculations (5). Additionally, the "cradle-to-grave" life cycle assessment was applied to analyze the environmental impacts of the ventilation system and its components throughout their entire life cycle.

3. Result

3.1. Danish school building

3.1.1 Quantity of key structural elements used in the building.

Figure 14 displays a graphical representation of key structural elements employed in the construction of Sofiendalskolen building. Notably, the case building exhibited minor variations in the quantities of building components utilized across various ventilation scenarios. In the Steel-ductwork Scenario, the total weight of structural elements amounts to 1205,58 kg/m2. Comparatively, in the Fabric ductwork Scenario, the total weight of structural elements slightly decreases to 1204,940795 kg/m2. Similarly, in the Glass-wool ductwork Scenario, the total weight of structural elements remains nearly unchanged at 1205,457499 kg/m2. Therefore, the choice of ventilation system design has a non-noticeable impact on the overall amount of structural elements. It is evident that the largest contributors to the overall amount of structural elements in the building are the foundations, internal walls, and external walls.

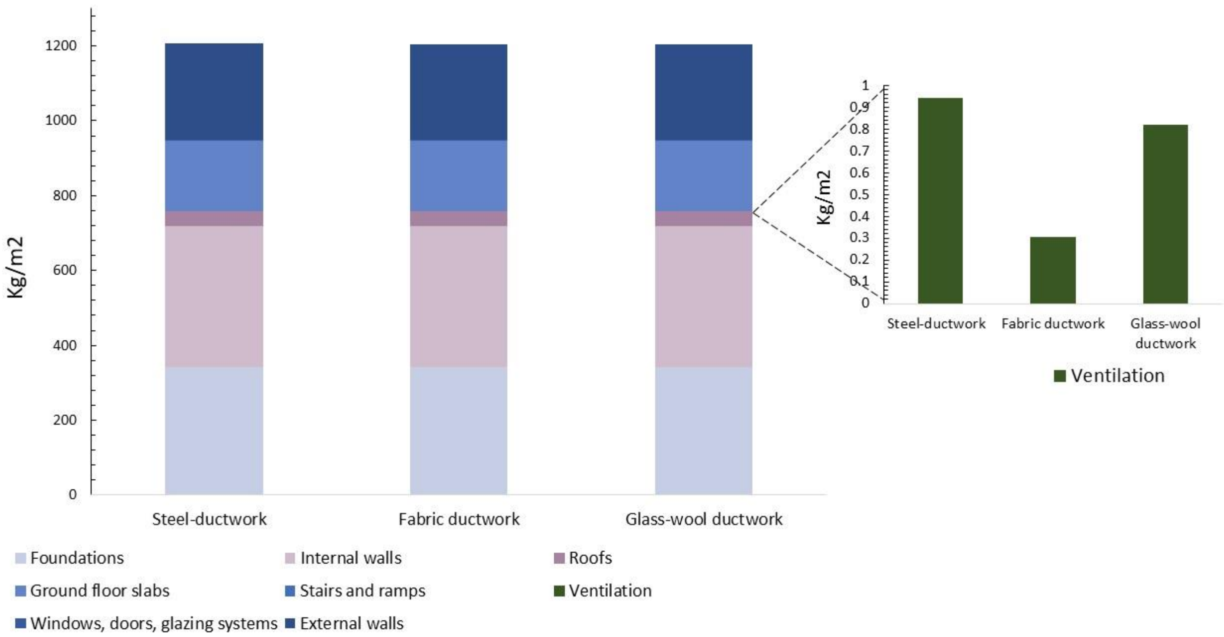

Figure 14: Quantity of key structural elements used in the school building (kg/m2).

3.1.2 CO_2 emission level at building level

Based on the results, it was determined that the selection of ductwork material within school ventilation systems can have a minor impact on embodied CO_2 emissions at the building level. When utilizing ductwork made of steel in a building, the estimated CO_2 emission for the entire building was approximately 6.58E+00 while ventilation accounts for approximately 1.376% of the total GWP in the building. The building has a total GWP of 6.53E+00, with ventilation contributing approximately 0.691% to this value when fabric ducting system applied in ventilation design. In contrast, the building designed with glass wool ductwork showed a higher GWP of 6.59E+00 compared to steel ductwork scenario. In this case, the ventilation accounts for 1.534% of the total GWP. Figure 15 reflects the relative contribution of each component to the overall GWP, with internal walls having the highest impact, followed by roofs, external walls, foundations, and finally windows, doors, and glazing systems having the lowest impact.

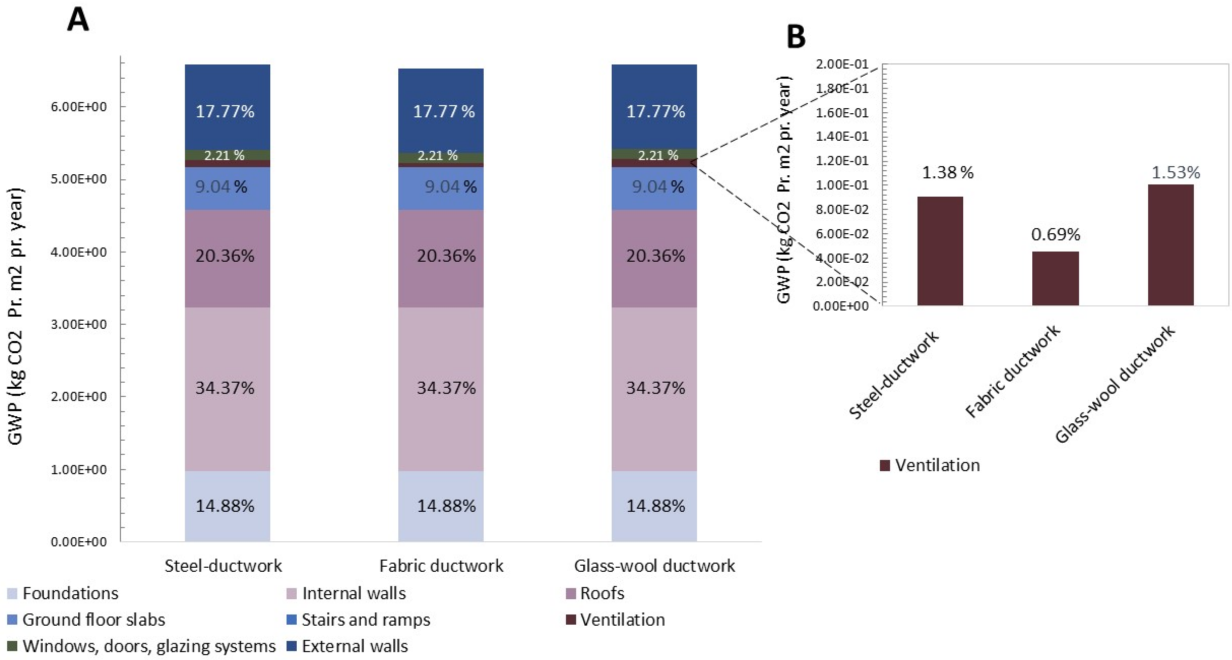

Figure 15: Relative contribution of each component to the overall GWP of the building (A), Relative contribution of ventilation system in the building (B).

3.1.3 Emission in ventilation components in different scenarios

As shown in figure 16, the AHU contributes significantly to the GWP in all three ventilation system scenarios. The steel ductwork alone contributes around 37% to this ventilation related GWP. While the fabric and glass wool ductwork component accounts for approximately 5% and 32% of the total GWP in the ventilation system respectively. Therefore, at ventilation level, fabric ductwork generally has the lowest GWP, while the glass wool ductwork scenario has the highest GWP contribution.

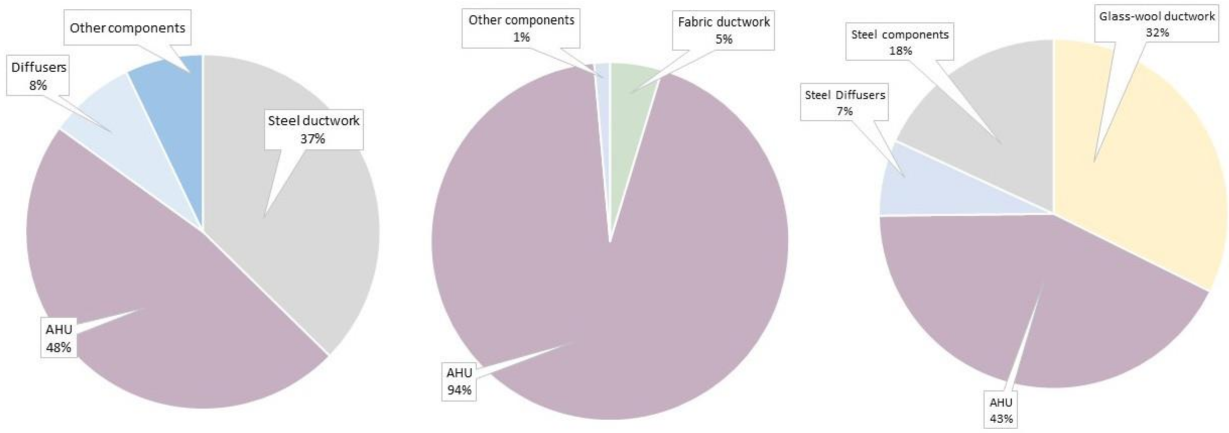

Figure 16: Co2 mission in ventilation components in different scenarios of steel ductwork, fabric ductwork and glass wool ductwork-based system (left to right).

3.1.4 Life cycle stage analysis

The data provided in figure 17 presents the results of a life cycle stage analysis for various components in the case building. Comparing the GWP values across the different life cycle stages, it can be observed that the highest emissions typically occur during the A1-A3 and C3 stages for most components. This indicates that the extraction of raw materials, manufacturing, transportation, and the use and maintenance of the components contribute the most to their overall greenhouse gas emissions. The negative GWP value for a wooden roof suggests the potential carbon sequestration effect where the component has the potential to remove or offset more CO2 from the atmosphere than it emits during its life cycle stages. Since wood, as a natural material, could store carbon dioxide through carbon sequestration during the growth phase of trees.

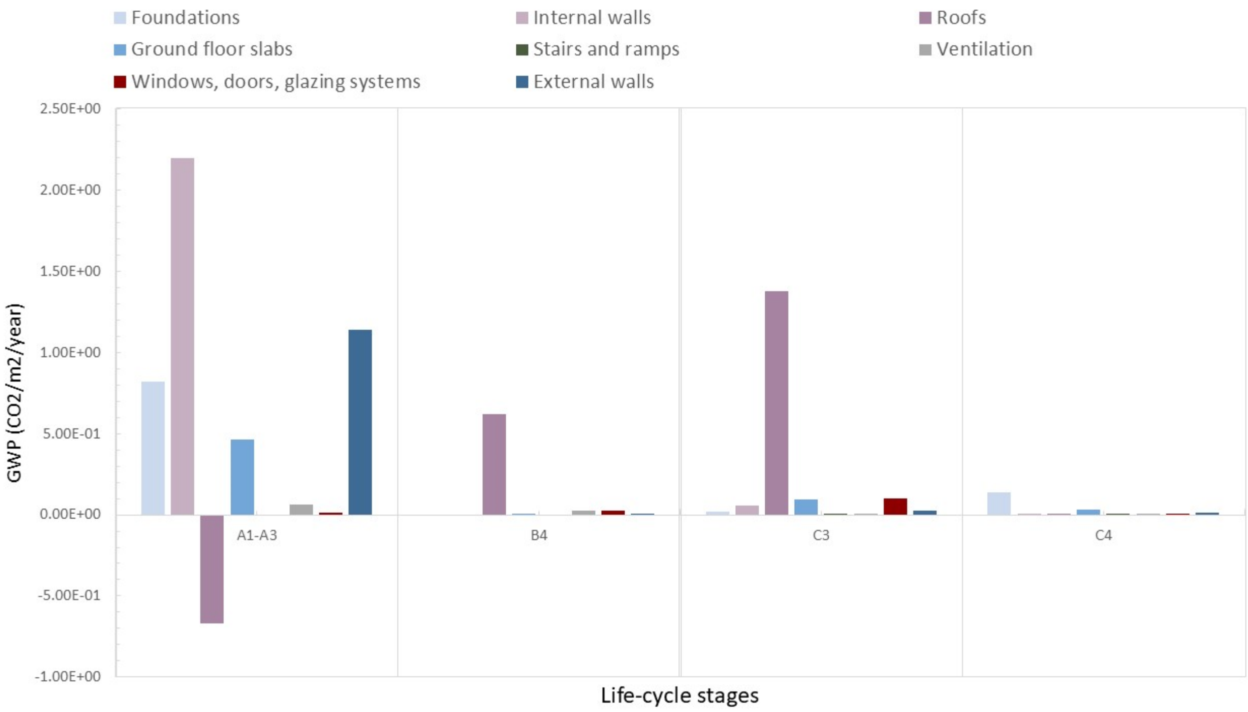

Figure 17: life cycle stage analysis of school building.

At ventilation system level, the Steel ductwork has the highest embodied CO2 emission indicating a relatively higher environmental impact during the early stages of its life cycle while fabric ducting showed approximately 66.18% lower GWP compared to the steel ductwork in the A1_A3 life cycle stage. The glass-wool duct exhibits a GWP of 5.97E-02 (figure 18).

Moving on to the B4 life cycle stage, the GWP values reveal that both the steel and fabric duct scenarios have comparable GWP values, with a percentage difference of approximately -9.96. Conversely, the Glass-wool duct scenario has a higher GWP compared to the Steel duct scenario, with a percentage difference of approximately 65.34%. In the C3 and C4 stages, all three scenarios exhibit very low GWP values, indicating minimal environmental impact during these phases.

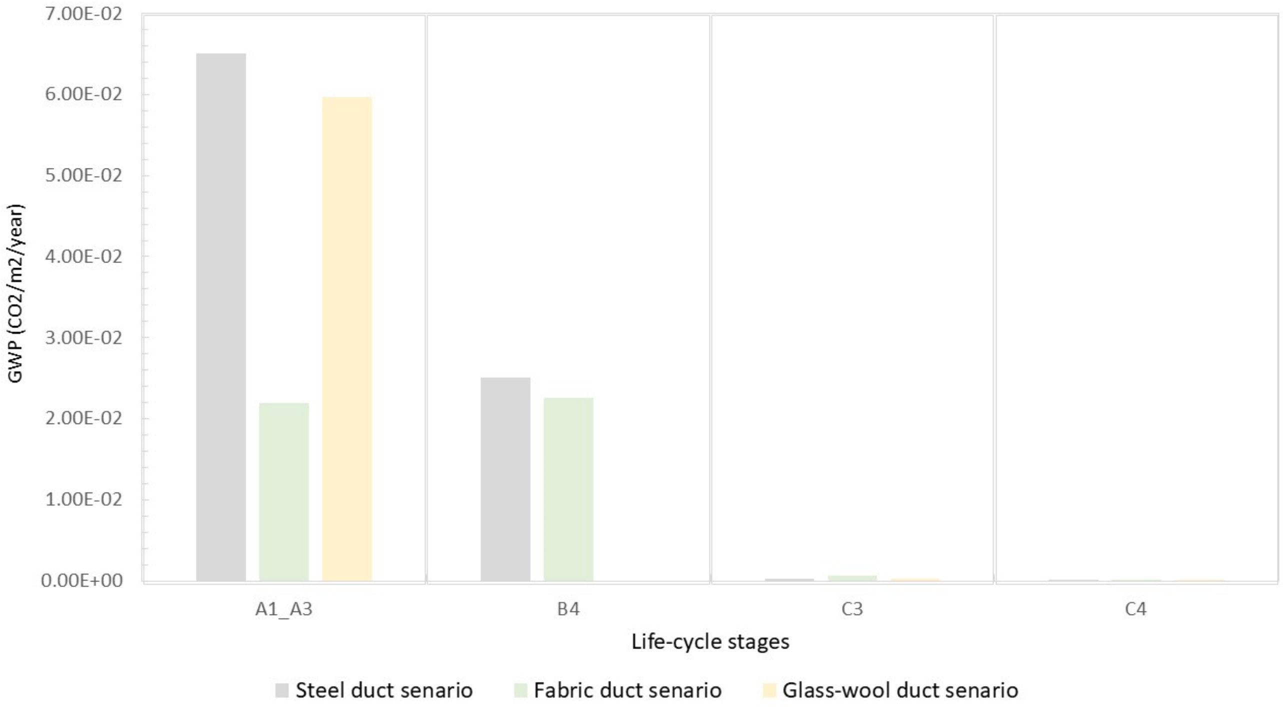

Figure 18: life cycle stage analysis of ventilation components.

3.2. City Campus Aalborg

3.2.1 Quantity of key structural elements used in the building.

The graph presented in figure 19 illustrates the quantity of key structural elements used in building construction measured in kilograms per square meter (kg/m2). It was observed that the quantities of building component used in City Campus Aalborg varied slightly among different ventilation scenarios. Specifically, the observations indicated that the utilization of steel-based ductwork amounted to approximately 4.16 kg/m2, while fabric ductwork accounted for approximately 1.16 kg per square meter. Additionally, the implementation of glass wool ductwork was observed to be approximately 3.89 kg/m2. A lower kg/m2 value indicates that fewer materials are required to construct a building, implying potential resource savings. Although, similar to the initial case study building, the specific materials and ventilation designs differed to some extent but the overall differences in quantities in building level were not significant.

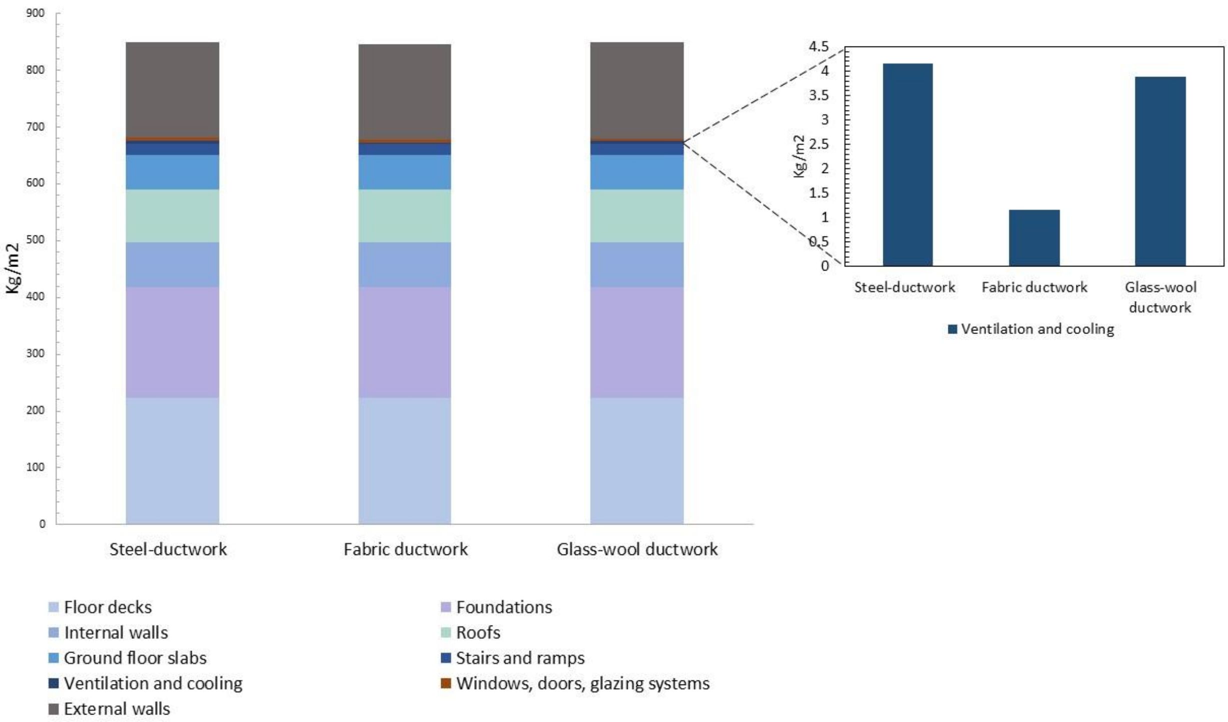

Figure 19:Left: The quantity of key structural elements used in building construction measured in kilograms per square meter (kg/m2). Right: The quantity of ventilation component in different ventilation scenarios(kg/m2).

3.2.2 CO2 emission level at building level

Upon evaluating the global warming potential (GWP), it was found that the choice of ductwork material in ventilation system could slightly influence the CO2 emission at the building level. When steel-based ductwork is employed in a building, the GWP of the whole building was estimated to be around 4.21 kg CO2/m2/year (figure 20) while approximately 9.73% of the total CO2 emissions in this scenario are attributed to the ventilation system. In contrast, when fabric ductwork was employed, the GWP decreased slightly to 4 kg CO2/m2 /year (figure 20). In this scenario, approximately 5.08% of the case CO2 emission is due to the fabric-based ventilation system. This indicates that fabric ductwork contributes less to global warming potential compared to steel-based ductwork.

Surprisingly, in the comparison between glass wool ductwork and steel-based ductwork, it is observed that glass wool ductwork has a slightly higher GWP (4.23 kg CO2/m2 /year) and approximately 10.32% of the building's global warming potential is due to the ventilation system.

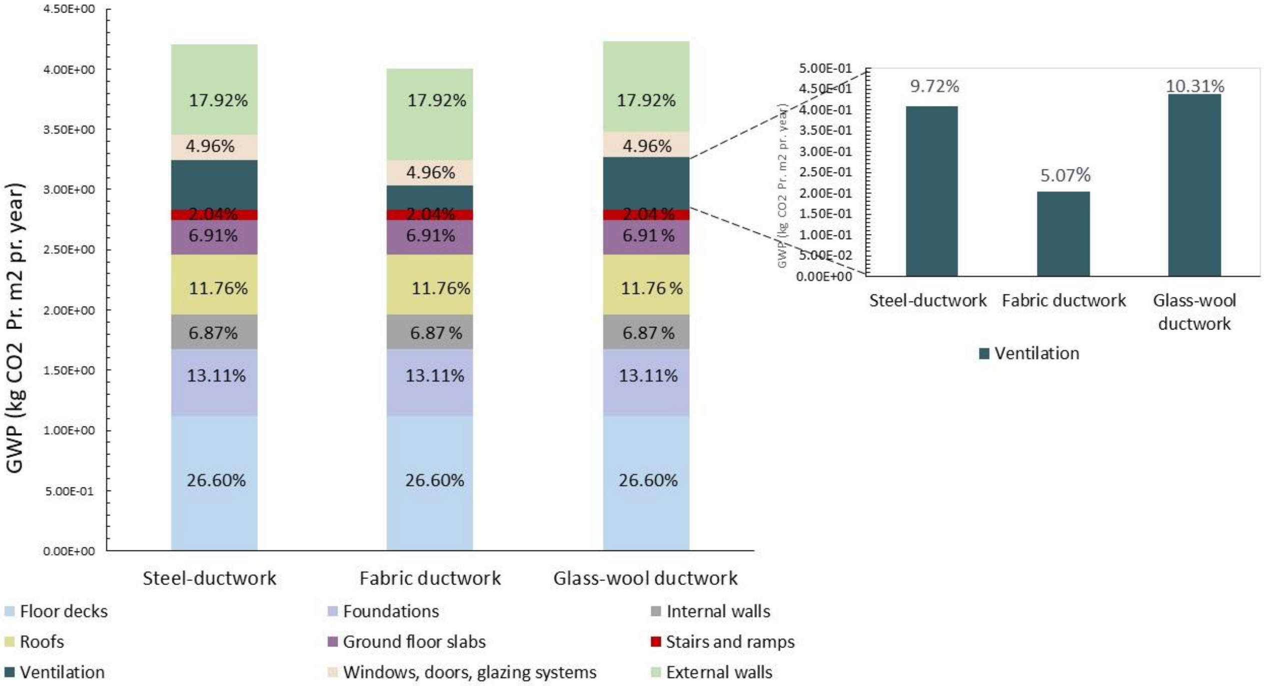

Figure 20: CO2 emission level (kg CO2/m2 /year) of City Campus Aalborg building by applying different ductwork in ventilation system.

3.2.3 CO2 Emission in Ventilation Components in Different Scenarios

In scenario A (figure 21A), which utilizes galvanized steel ducts, the air handling unit contributes 47%, the diffusers contribute 4%, the steel ductwork contributes 42%, and other components contribute 7% to the total embodied CO2 emissions related of ventilation system. In contrast, Scenario B (figure 21B), which employs fabric ducts, the air handling unit becomes the dominant contributor, responsible for a staggering 96% of the CO2 emissions. Interestingly, the fabric ductwork, which is the main difference in this scenario, contributes only 4% to the emissions.

In scenario C (figure 21C), which involves glass-wool ducts, the air handling unit remains a substantial contributor, accounting for 44% of the embodied CO2 emissions. Similarly, to Scenario A, the diffusers contribute 4% to the total emissions. However, in Scenario C, the glass wool ductwork itself becomes a more significant contributor, responsible for 17% of the emissions. Additionally, steel components contribute 35% of the CO2 emissions in this scenario.

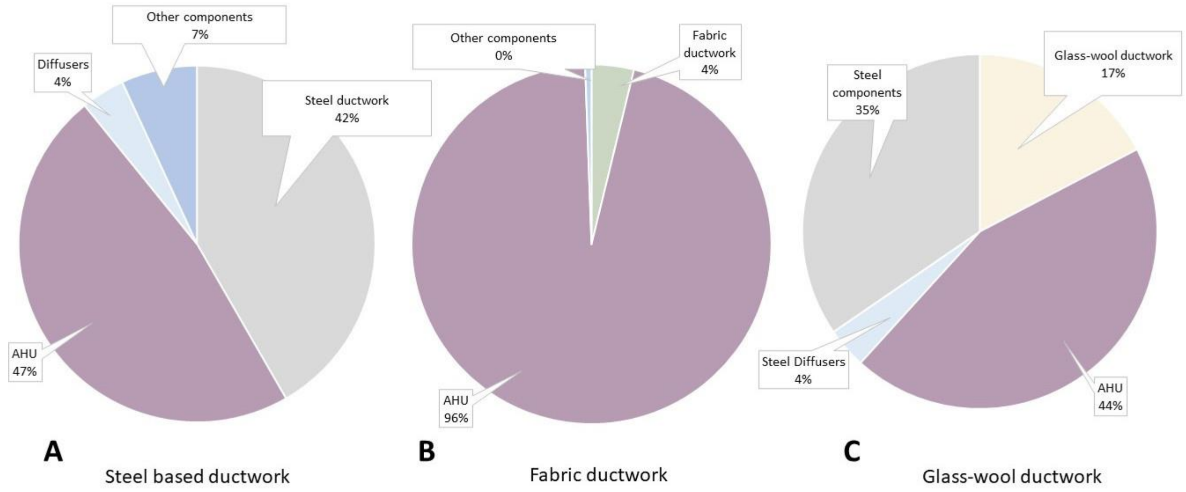

Figure 21:Embodied CO2 Emission in ventilation components in different scenarios

3.2.4 Life cycle stage analysis

Based on the results presented in figure 22, the production stage (A1-A3) has the highest overall impact in CO2 emissions for most of the building components. However, for some components, replacement of component (B4) waste processing and disposal (C3-C4) of materials also contribute to the total embodied CO2 emissions. Among all building components, the floor decks have the highest CO2 in the production stage followed by external walls. Roofs, foundations, and ventilation systems have moderate impacts, while internal walls, ground floor slabs, stairs and ramps, and windows, doors, and glazing systems have comparatively lower impacts.

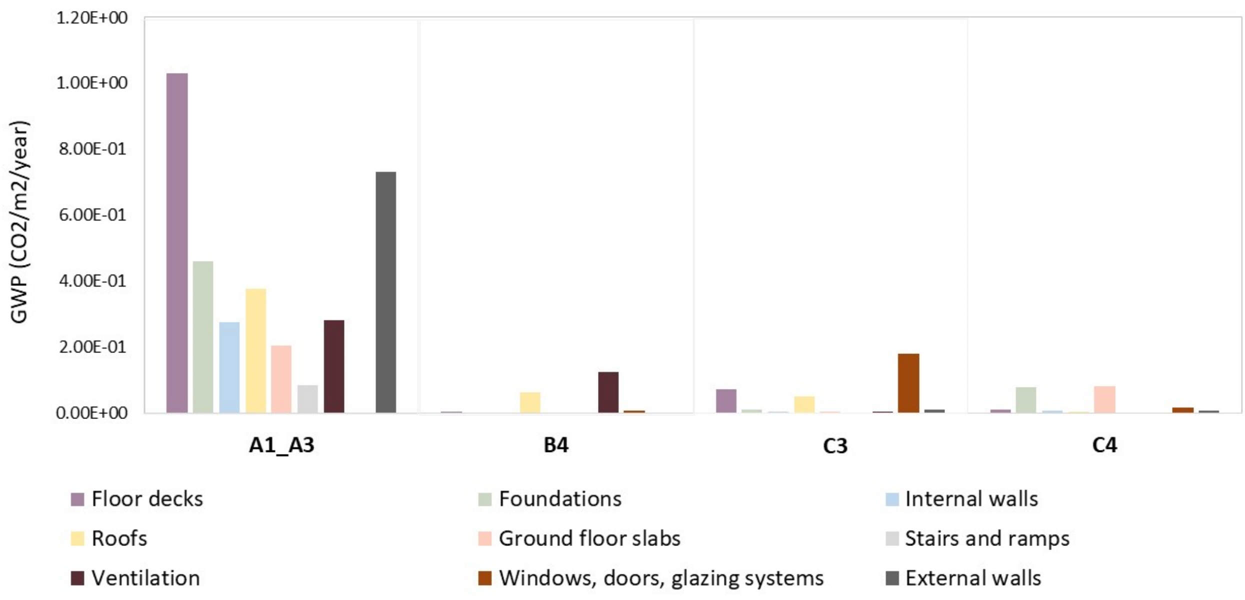

Figure 22: GWP of building component in different life cycle stages.

The results obtained from life cycle stage analysis of ventilation components show that in the A1-A3 stage, the steel duct scenario emits the highest amount of CO_2, with a value of 2.82E-01. The fabric duct scenario has the lowest emissions in this stage, with a value of 7.90E-02. Therefore, percentage reduction in CO_2 emissions by choosing fabric ductwork over steel ductwork in the A1-A3 stage is approximately 71.99%. while the percentage reduction in CO_2 emissions by choosing glass-wool ductwork over steel ductwork in the A1-A3 stage was only 3.55%.

During the B4 stage, which involves potential component replacement or repair, the emissions for all scenarios are relatively close, ranging from 1.19E-01 to 1.62E-01. The higher CO_2 emissions was observed in the glass-wool duct scenario, while the lower CO_2 emissions was observed in the fabric duct scenario during the B4 stage.

In the C3 stage, which focuses on waste processing, the fabric duct emits the highest amount of CO_2, with a value of 4.32E-03 and the steel duct scenario has the lowest emissions in this stage, with a value of 3.44E-03. The glass-wool duct scenario emits 3.12E-03. Lastly, the C4 stage, which pertains to the disposal of materials, showcases consistent emissions across all scenarios, with a value of approximately 3.25E-04.

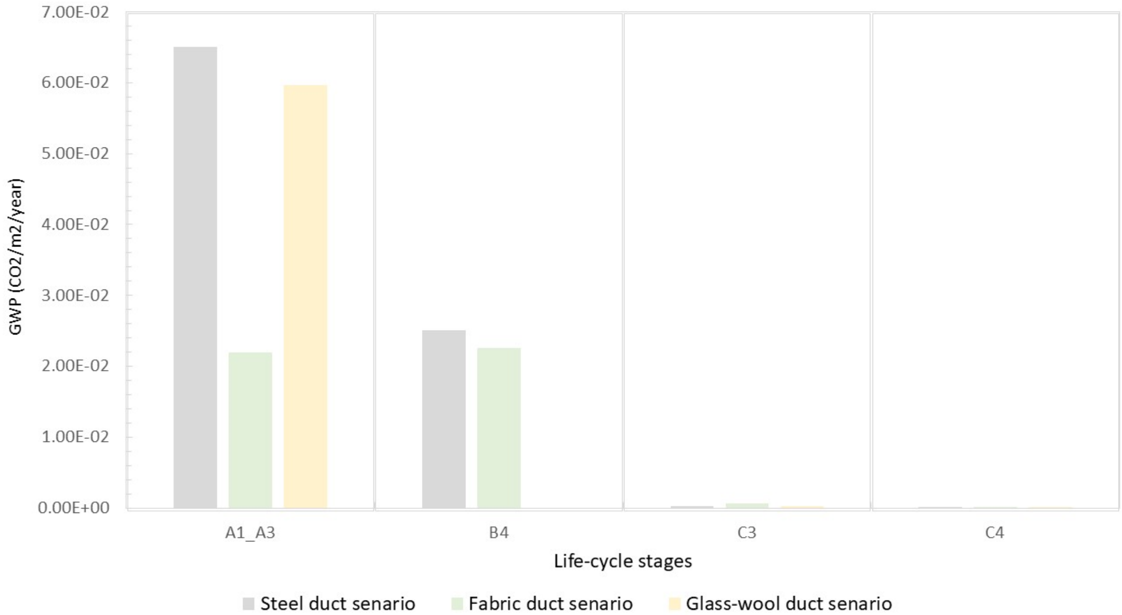

Figure 23: GWP of ventilation component associated to different scenario of steel based, fabric and glass-wool ductwork in different life cycle stages.

4. Discussion

4.1. Key findings

4.1.1 Impact of ventilation design in amount of structural elements used in building.

It was evident that the largest contributors to the overall amount of structural elements in both case buildings were foundations, external walls, internal walls and floor decks and the choice of ventilation system design had a non-noticeable impact on the overall amount of structural elements used in building construction measured in kilograms per square meter (kg/m2/year).

4.1.2 CO2 emission at building level

School with a GWP of 6.58E+00 (per m2), exhibited slightly higher CO2 emissions compared to City Campus Aalborg, which had a GWP of 4.21 (per m2). This indicated that, on a per square meter basis, City Campus Aalborg has a lower environmental impact in terms of embodied CO2 emissions. Most likely, the higher GWP per m2 in school influenced by the materials used in its construction. For instance, the school's roof is made of wood, carbon sequestration effect, it had a significantly higher GWP during B4 and C3 stage figure X.
On the other hand, external and internal walls are made of brick in school. While City Campus Aalborg has opted for precast concrete walls. Concrete generally has a lower GWP compared to wood during its production and end-of-life stages figure X. The manufacturing process of precast concrete typically involves less carbon emissions, and concrete can also have a longer lifespan and be easily recycled at the end of its useful life, reducing its environmental impact. Considering these differences in material choices, City Campus Aalborg demonstrates a lower environmental impact in terms of embodied CO2 emissions per square meter. The school with an area of 2618 m2, would have a total estimated CO2 emission of approximately 17,202.44 kg CO2/year. On the other hand, City Campus Aalborg, with an area of 20,000 m2, would have a total estimated CO2 emission of approximately 84,200 kg CO2/year.
At building level, a minor difference in CO2 emissions was observed based on the selection of ductwork material in their ventilation systems. School building demonstrated that fabric ductwork resulted in slightly lower CO2 emissions compared to steel-based ductwork. However, City Campus Aalborg showed a more significant reduction in CO2 emissions with fabric ductwork. Notably, the use of glass wool ductwork in both buildings led to slightly higher CO2 emissions compared to steel ductwork scenarios. It is worth noting that the use of glass wool ductwork in both buildings led to higher CO2 emissions compared to scenarios where steel ductwork was employed.

4.1.3 CO2 mission in ventilation system level

Generally, at the ventilation system level, the AHU had the highest contribution to the GWP in the ventilation system, followed by other components such as diffusers, ductwork, and other materials. Based on obtained results, fabric ductwork had the significantly lower GWP values in both case buildings. Despite the need for replacement more often, fabric ductwork has a smaller environmental footprint compared to steel and glass-wool ductwork. Life cycle stage assessment also showed that fabric ductwork has a significantly lower CO2 emission during the early stages of its life cycle. Therefore, fabric ductwork emerges as the most favorable option in terms of environmental considerations for the ventilation system.

The results indicated that in both buildings, glass wool ductwork had the highest GWP contribution among the three options. In the case of steel ductwork compared to glass wool ductwork, there are some notable distinctions. During the A1-A3 stage, steel ductwork tends to have a higher GWP than glass wool ductwork. This is primarily because steel production is energy-intensive and often involves the extraction of iron ore, which contributes to greenhouse gas emissions. However, the scenario changes in the B4 stage. Here, the GWP of glass wool ductwork becomes higher due to the need for replacement after approximately 30 years. Glass wool ductwork has a limited lifespan compared to steel. Consequently, the frequent replacement of glass wool ductwork results in additional manufacturing processes, transportation, and associated emissions over time.

Therefore, when assessing the GWP of a ventilation system that utilizes glass wool ductwork, the cumulative impact over the system's lifespan becomes higher due to the need for replacements. In contrast, steel ductwork, while having a higher GWP in the early stages, offers a longer lifespan and requires fewer replacements, resulting in a lower overall GWP. Therefore, from an emissions perspective, glass wool ductwork may not be the most environmentally friendly choice for a ventilation system.

5. Conclusion

In conclusion, this thesis conducted a comprehensive comparative life cycle assessment (LCA) to evaluate advanced alternatives to traditional ductwork for ventilation systems in Danish commercial buildings. The research focused on assessing the global warming potential (GWP) of ductwork made from Tailor-Made Fabric, Glass Wool, and Galvanized Steel.

The findings revealed that the choice of ventilation system design had a non-noticeable impact on the overall amount of structural elements used in building construction. However, in terms of embodied CO2 emissions, City Campus Aalborg exhibited a lower environmental impact compared to the school due to its material choices, such as precast concrete walls with lower GWP.

At the ventilation system level, the air handling unit (AHU) was found to have the highest contribution to the GWP, followed by other components such as diffusers, ductwork, and other materials. Fabric ductwork emerged as the most favorable option from an environmental perspective, despite the need for more frequent replacements. It exhibited lower CO2 emissions during the early stages of its life cycle. On the other hand, glass wool ductwork had the highest GWP contribution among the three options due to the need for frequent replacements, offsetting its initial lower emissions during production.

These findings highlight the importance of considering the entire life cycle of ductwork materials when assessing their environmental impact. Fabric ductwork shows promise as a more sustainable option, offering lower CO2 emissions and a smaller environmental footprint compared to steel and glass wool ductwork. Furthermore, the study highlighted the limitations of glass wool ductwork in terms of its higher GWP contribution over the system's lifespan due to frequent replacements, while steel ductwork, despite higher GWP in the early stages, offers a longer lifespan and lower overall GWP. Therefore, glass wool ductwork may not be the most environmentally friendly choice for a ventilation system when considering emissions. The results of this study provide valuable insights for decision-makers in the selection of materials for ventilation systems, promoting more sustainable building practices and reducing environmental impact in the Danish context. Further research and development in this area can contribute to even more eco-friendly alternatives for ductwork in commercial buildings.

6. Future research potential

Based on the findings and conclusions of this thesis, several future research suggestions can be proposed to further enhance our understanding of advanced alternatives for ductwork in ventilation systems:

- Extended Life Cycle Assessment (LCA): To conduct a more detailed and comprehensive life cycle assessment that considers a broader range of environmental impact categories beyond global warming potential (GWP).
- Comparative Cost Analysis: Explore the economic aspects of using advanced ductwork materials compared to traditional galvanized steel ductwork. This analysis can help decision-makers understand the economic viability of sustainable ductwork materials and promote their adoption in commercial buildings.
- Innovative Ductwork Materials: to explore emerging materials and technologies for ductwork that have the potential to further enhance environmental performance.

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