Assessment of embodied carbon of ventilation systems and their components in educational and office buildings

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ARTICLE INFO

Relevant journals:
Building and Environment
Energy and Buildings

Article history:
Submitted: 7 January 2022

Keywords:
Embodied carbon
Ventilation system
Life Cycle Assessment (LCA)
Global Warming Potential (GWP)
Material composition
Carbon reduction

ABSTRACT

The Climate Act approved by the Danish government and the subsequent initiation of CO_2 emission limits for buildings in the Danish Building Regulations by 2023 set the target for research in this area. The currently published studies lack in focus on the HVAC systems, especially in relation to the embodied carbon. This study aims to assess the embodied carbon of ventilation systems in educational and office buildings. The currently available environmental data on the ventilation systems is insufficient to conduct a reliable assessment, therefore a detailed assessment based on component specific quantities and material composition was carried out. The generalised results from the assessment of three case-buildings set new GWP reference values for the ventilation system and its components, applicable for buildings falling under the investigated building category. The findings of the study also highlight the critical components of the system in terms of their embodied carbon, followed by investigation into the carbon reduction potential of these. The results of this investigation lead to suggestions of necessary actions to be taken within the industry to reduce the environmental impact of ventilation systems and components.

1. Introduction

The Danish government has recently approved a Climate Act, which aims to reduce the CO_2 emissions in Denmark by 70% by 2030 in comparison with 1990.

The plan of action for the construction sector is described in the National Strategy for Sustainable Construction, where one of the steps is the launch of The voluntary sustainability standard in 2020. The idea behind the standard was to introduce its principles and incorporate them into the Danish building regulations by 2023, during a two-year test period. The new threshold limit for buildings bigger than 1000 m^2 is set to 12 kg CO_2 eq./m^2/year, where buildings smaller than 1000 m^2 only have requirements for LCA calculation. This requirement regarding CO_2 emissions in new buildings will gradually become stricter, where the threshold value decreases to 10.5 kg CO_2 eq./m^2/year in 2025, 9 kg CO_2 eq./m^2/year in 2027 and 7.5 kg CO_2 eq./m^2/year in 2029, regardless of the building size. [1]

The current Danish building regulations (BR18 [2]) already address areas that have influence on the environmental impact of buildings, but they are limited to the use of operational energy, where the embodied energy of the construction materials themselves is overlooked. As the study on the climate impact of 60 Danish case buildings [3] points out, the impact from the building materials (embodied carbon) is generally 2-4 times higher (in kg CO_2 eq./m^2/year) compared to the impact from operation of a building for investigated reference study period of 50 and 80 years. Another issue the study highlighted is the lack of data for technical installations necessary for accurate estimation of the embodied carbon.

The aim of this study is therefore to reduce the above mentioned information gap concerning mechanical ventilation systems. The focus is on detailed embodied carbon assessment of ventilation systems in educational and office buildings and the overall share of different ventilation components in order to identify the critical parts with the highest contribution to the total environmental impact as well as to show the focus points for potential improvements.

The paper is divided into six sections, where Section 2 introduces the theoretical background of the subject with focus on embodied energy and HVAC systems. Section 3 outlines the methodology followed in this study. The results are presented in Section 4, where the Global Warming Potential (GWP) is quantified for the investigated ventilation systems and their components with the use of Life Cycle Assessment (LCA) method. Based on the assessment results, the critical areas of ventilation system are identified and their potential for carbon reduction is analysed. The interpretation of the results is discussed in Section 5, including the limitations of the study, and Section 6 summarizes the key findings and recommendations.

2. Theoretical background

For the past four decades, climate change and environmental degradation have become a major global concern. The interest in global energy consumption reduction as means of fighting these effects has been increasing exponentially since the early 1980s. The focus has been put on the building sector as one of the main contributors to the global CO_2 emissions (40%). This, in addition to the fact that the building industry is responsible for 60% of raw material consumption and 35% of waste generation, as well as 50% of water consumption shows the impact the building sector has on the climate change. [4] [5] [6] [7] [8] [9] [10]

2.1. Operating vs. embodied energy

The global and European efforts in reducing the environmental impact of the building sector have been mainly focused on reduction of operational greenhouse gas (GHG) emissions so far. As the studies [11] and [5] point out, this focus is being reflected in the research and practice as well, where strategies for operational energy-efficiency have been implemented and executed successfully in the past decades. As a result, however, the share of embodied energy in the life cycle of buildings has increased, since implementing said energy-efficiency strategies requires increase in material use (external shading devices, increased insulation thickness in facades, energy-efficient windows, higher demands for mechanical ventilation,…), translating into higher embodied energy in projects.

The embodied carbon in energy efficient buildings as estimated by study [4] can have a contribution of up to 80% of their total lifetime GHG emissions. The share of embodied carbon in the total life cycle carbon emissions of a building can however vary depending on the building type and its function, the climate and location of the building, its material construction and orientation among others, as reported by study [9].

Study [12] performs literature review on 60 conventional and low energy buildings to analyse the environmental impact of both embodied and operational energy. The findings of this research show that the embodied energy is responsible for 2% to 38% of total energy use in conventional buildings and 9% to 46% in low - energy buildings.

Similar study analyses the embodied energy of 73 office and residential buildings and shows that the embodied energy is responsible for 10–20% of the total energy use of the buildings [13].

The area of research and practice concerning the operational energy is a robust area as demonstrated by study [11], where the needed tools to assess and optimize the operational energy in buildings are available, in terms of accurate data, methodologies, technology, codes and guidelines. In regard to embodied energy, however, the necessary tools and methods are not globally consistent or fully developed, which often results in unreliable and inaccurate results.

Study [6] describes the environmental impact of embodied energy of key materials in building sector as an overlooked aspect in building’s carbon footprint assessment. It highlights the importance of considering the impact of the embodied energy in the design stage of the building process, while also taking into account the operational energy which has higher environmental impact throughout the life cycle of buildings. The study demonstrates that the reduction of operational energy in highly energy efficient buildings can be done to a limited extend. Therefore, efforts in the future should be directed to the reduction of the embodied carbon, which should be considered in early stages of the construction process. This can be applied at the design phase in the form of making the correct decision when selecting the materials.

2.2. Life Cycle Assessment and environmental aspects

The successful progress in reduction of the operational energy use in buildings in the recent years and the arising awareness of the importance of embodied energy share in the total environmental impact of the whole life cycle of a building has therefore caused a shift in attention towards this issue [9]. Many recent studies such as [5] and [14] show that a building cannot be labelled as sustainable only because it has a low energy consumption, since the entire life cycle would not be considered in the assessment, only the use phase. The design of low-carbon emission buildings needs to consider all aspects of the construction process including sourcing of the raw materials, production of components, their transport, maintenance and waste, in addition to the use of the building. Likewise, different environmental aspects should be also part of the assessment, minimising the risk of sub-optimisation, where efforts to reduce the impact of one of the aspects can result in negative effects on other environmental aspects/life cycle stages. However, study [6] determines carbon quantification as a major metric of environmental performance and energy efficiency, placing its impact above the other environmental aspects.

A globally accepted method for assessment of the environmental impact throughout a building´s life cycle and subsequent communication of the results is called Life Cycle Assessment (LCA). As the authors however point out in their study [8], the application of LCAs in the global building sector still has no clear and accepted methodologies, especially concerning the use of different LCA tools, where the boundary conditions, impact categories or functional unit may vary from study to study. Another issue identified in the research paper are the uncertainties when conducting an LCA, where it is recommended to conduct a sensitivity analysis as part of the assessment, in order to improve the accuracy of the results.

Study [8] concludes that one of the gaps that has been brought into the light across different studies is the significant difference in the embodied energy calculations in terms of system boundaries and functional units, which results in large deviations between the results and difficulties in comparing and validating them. Applying different methodologies and different databases in assessment of the embodied energy of materials might give various results, as mentioned in study [6].

The deviations in the documented quantity of embodied energy of buildings have been addressed in different literatures as highlighted by the authors in study [11]. The reasons according to the study are the variations in system boundaries, estimation methodologies, data source, geographical and technological representativeness.

Study [15] draws attention to the lack of Environmental product declarations (EPDs) for building materials that are essential in LCA assessment. Denmark’s neighbouring countries such as Norway, Sweden and Germany have a relatively high rate of availability in terms of EPDs for building materials, however the rate of availability is gradually rising in Denmark as well.

2.3. HVAC systems focused LCA

Many of the studies on the topic focus on general assessment of a building, often simplifying or omitting certain systems, such as the heating, cooling and air conditioning (HVAC). The scope of the majority of the LCA studies is the environmental impact of the general structure of the building envelope, while the studies that focus on HVAC systems are very rare and undetailed as addressed in studies [4] and [16].

The HVAC systems are however one of the large contributors to the total potential environmental impact in the building sector. This is shown in studies [16] and [7], where they investigate the importance of the construction of HVAC systems and its impact on the environment. The manufacture, transportation and installation of these systems have a high carbon footprint that should not be underestimated, on the contrary, a sustainable ventilation method is highlighted as one of the possible strategies to reduce carbon emissions in buildings. In addition, the studies that deal with the LCA assessment of different alternative ventilation systems, in terms of carbon emissions, are very limited, according to study [7].

There are studies that have assessed the environmental impact of commercial buildings (offices, health cares, etc.) in regard to carbon emissions. The gathered studies from the reviewed literature analyse the embodied energy of HVAC systems and the share of it to the total environmental impact in the whole building's life cycle.

Study [4] has analysed the embodied impact of HVAC system in an office building situated in Switzerland. All the necessary information needed to conduct a life cycle assessment was taken from manufacturers and project documentation, supplemented with data from BIM model. The results from the assessment were compared with the target values from SIA 2040 (Swiss Energy Efficiency Path), revealing that the embodied energy of HVAC systems is triple compared to the defined goal and it accounts for 15% to 36% of the total embodied energy of the office building.

Another study analyses the embodied carbon of HVAC system in six healthcare centres located in Spain [5]. Based on the results, the embodied carbon for HVAC systems with lifespan of 15 years is around 48.95 kg CO_2-eq/m^2 and this value can be compared with the building's operational CO_2 emissions for 2.3 years of use.

Furthermore, study [16] assesses the embodied emissions of three ventilation systems (VAV system, chilled beam and an underfloor air distribution) of an office building located in Melbourne, Australia, with reference study period of 50 years. Based on the results, the study concluded that all the above-mentioned systems have high contribution in regard to total carbon emissions, however the highest of all is the chilled beam system.

Another important study focuses on the building materials and technical installations in an office building in Sweden [14]. The purpose of this study is to show the parts that contribute more to several impact categories. The lifespan of the building is set to 50 years. The most essential findings are referring to HVAC systems that have a significant contribution to the total environmental impact, mainly due to replacement. Also, the study shows that the HVAC systems are responsible for 14% to 32% in four out of five impact categories, highlighting the importance of HVAC system in the life cycle assessment.

2.4. Carbon reduction

Understanding the critical areas of the system and its impact reduction opportunities provides a strong foundation for strategic and informed decisions in different stages of the design and building process, as implied in study [17].

Study [9] compiles and summarizes different embodied carbon reduction strategies in buildings and groups them into five categories, these being use of low-carbon materials, strategies for material quantity reduction, strategies involving recycling and material reuse, minimization of transport, and strategies regarding the construction process itself. The concepts presented in the study are focused on building in general and more specifically on its structural elements, but some are applicable for mechanical building systems as well.

3. Methodology

3.1. Goal and scope

The goal of the project is to estimate the GWP (carbon emissions) impact from the ventilation system and its components for different case-buildings individually and find a generalized impact of a said building type. In addition, the aim is to identify the critical components and to examine the available options for carbon reduction of these components.

The project is defined by the following system boundaries:
The investigated buildings were educational and office buildings of varying sizes (8000 m^2 - 10,000 m^2) situated in Denmark and ventilated mechanically.

The focus of this project is the embodied carbon of the ventilation systems which translates into the environmental impact category of GWP measured in [kg CO_2 eq.]. The remaining impact category indicators were excluded from the scope of the project.

The reference study period for the assessment is 50 years as recommended by the Danish agency for housing and planning for Voluntary Sustainability Class calculations [18].

In this project, the "cradle-to-grave" life cycle assessment was applied, investigating the stages/modules in the life cycle from the resource extraction ("cradle") to the disposal phase ("grave") [19]. The modules included in the assessment were the Product stage (A1-A3), Construction stage (A4-A5), Use stage - Replacement (B4) and End of life stage (C3-C4) as specified by the Danish agency for housing and planning for Voluntary Sustainability Class calculations [18]. The use stage – Operational energy use (B6) was excluded from the assessment, since the focus of the project is only the embodied carbon. [20]

The functional unit used in this project in order to establish functional equivalency between the investigated case-buildings was set to 1 m^3/h airflow per 1 m^2 of heated floor area for a reference study period of 50 years. The results of the investigation were expressed in [kg CO_2 eq./m^3/h m^2], where [kg CO_2 eq.] is the unit for the investigated category indicator of GWP, since the focus of the project is the embodied carbon of the ventilation systems.

The following cut-off criteria were applied for the assessment:
The investigated area of the building was the ventilation system and its components only, any other HVAC systems (heating) and their components were not included in the assessment.

Only the ventilation components defined and specified in the 3D ventilation model were included in the inventory for the analysis, any components related to the electrical model (wiring, control systems,…) and/or fire safety were excluded.

Regarding the material composition of the components, all the materials that have higher than 1% share of the total component weight were included in the calculations. Heating/cooling mediums running through the component under operation were not included in the calculations due to insufficient information.

3.2. Inventory analysis

The BIM model and the project documentation for each case-building served as a base for quantifying the ventilation components and to define the building type, size, and other building properties.

Only the components contained in the 3D BIM model and the information included in them were considered. All the components were grouped in relevant categories, these being ducts & fittings, accessories, terminal units and air handling units. (The duct accessories category does not include any components related to fire and smoke strategies.) Schedules were made for each category, containing information on the component's producer, model, size and quantity. Where there was no information attached to the component (generic component, not defining the producer, type,…) assumptions regarding this information were made considering the availability and accessibility of such information from different producers in Denmark.

Quantity schedules were then exported from Revit to Excel, where the data was filtered and treated, depending on the required detail level for the LCA calculations.

Material composition was defined for each component listed in the schedules, based on the EPDs and datasheets provided by the manufacturer.

Detailed description of the data extraction and treatment process can be found in Appendix 1, Methodology, Data extraction. The list of all the components, their type, size and quantities can be found in Appendix 2, Data extraction. Data sheets and EPDs used for the calculations can be found in Appendix 2, Data sheets & EPDs.

3.3. Impact assessment

The impact assessment for this project was done using LCAbyg tool.

LCAbyg is a danish LCA calculation software that based on the user input regarding the building and building components (construction type, quantity, service life,…) uses the software´s database in addition to ÖKOBAUDAT [21] database information to calculate the environmental impact in different Life Cycle stages. The results obtained from the calculation are the material quantities and the environmental impact for the included elements.

The assessment for each case-building consisted of two different detail levels (generic assessment & detailed assessment), where the quantity input for calculations for both detail levels was based on the values extracted during inventory analysis.

The generic assessment was based on the generic data available in the ÖKOBAUDAT [21] database and the pre-set component properties in LCAbyg. The list of components and their properties from the Inventory Analysis was used as a guideline for finding the most relevant components in the database and to estimate their quantity. Due to the lack of available ventilation components in the existing database, the generic assessment model was built as a simplified version of the project´s ventilation system. The model included only the ductwork and AHUs. Certain component categories were left out from the assessment altogether, since no applicable components, such as terminal units and duct accessories, can be found in the database.

The detailed assessment model was based on the detailed data from the Inventory analysis, consisting of definition of all the components, their properties and quantities. The impact of each component was calculated using its material share found in the EPDs and other documentation. The environmental indicator values of each material come from the ÖKOBAUDAT database [21] or the specific environmental data given by manufacturer. The service-life of the components used in the calculations, if not specified in the EPDs or datasheets, came from ASHRAE Equipment Life Expectancy chart [22], since the Danish equivalent [23] does not contain detailed ventilation component information.

For both, Generic and detailed assessment, the numbers for waste and transport (10% and 500 km respectively) used in the calculations are the recommended values by Danish agency for housing and planning for Voluntary Sustainability Class calculations [18] for cases where the actual values are unknown. Stated values were used for all the case-buildings, to ensure functional equivalency as described in the Goal and Scope definition.

The assessment for the carbon reduction options in the ventilation system was carried out using the LCAbyg tool, where the impact of the different alternatives for the critical components was examined in connection with other parameters as well.

Detailed description of the process can be found in Appendix 1. The input values and the calculation results for both generic assessment and detailed assessment models can be found in Appendix 2, LCAbyg results.

3.4. Interpretation

The results acquired in the Impact Assessment phase were interpreted for each of the case-buildings separately. The interpretation was done on different levels, one evaluating the total impact of ventilation on the system level, one on the component level and one on material level.

The results for all the case-buildings were then generalized by calculating the total weight and GWP of ventilation systems per functional unit in specified type of buildings (educational and office buildings). The results for both the weight and GWP are the accumulated values over the entire reference study period.

The interpretation results for each case-building can be found in Appendix 1, Life Cycle Assessment.

4. Results

4.1. Generic assessment vs. detailed assessment

As described in Section 3, the assessment for all the investigated case buildings have been done on two different detail levels, generic assessment and detailed assessment, where their results are then compared to each other. The goal of the comparison is to determine whether the generic assessment calculations are accurate enough and could be possibly used for a reasonably reliable environmental assessment of the ventilation systems.

In order to assess the extent of deviation between the two different levels, the detailed assessment results are set as 100% (representing the most accurate version of the ventilation system model) and the generic assessment results are expressed as a percentage of the detailed assessment results, showing the deviation. This method is applied for all the investigated cases, both on system level and on component level. (Figure 1 & Figure 2)

The results show relatively small deviation of the generic assessment calculations from the reference values of detailed assessment in the total weight of the ventilation system in all the cases. These results however, do not reflect the extent of overestimation/underestimation on the component level, where there is an extensive overestimation of weight of the ductwork, being almost doubled compared to detailed assessment and a significant underestimation of the weight of AHUs. In addition, there is an absence of duct accessories and terminal units from the generic assessment calculation altogether. (Figure 1)

The same applies when considering the results of GWP, where the environmental impact is dependent on the weight of the assessed system in combination with other parameters. (Figure 2)

The investigation into the two different detail levels and the quality of the results that can be obtained point out that generic assessment calculations are not accurate enough to be used for appropriate environmental assessment of the ventilation systems. Therefore, the next section will present detailed investigation of the detailed assessment results in order to set a baseline data for further use.

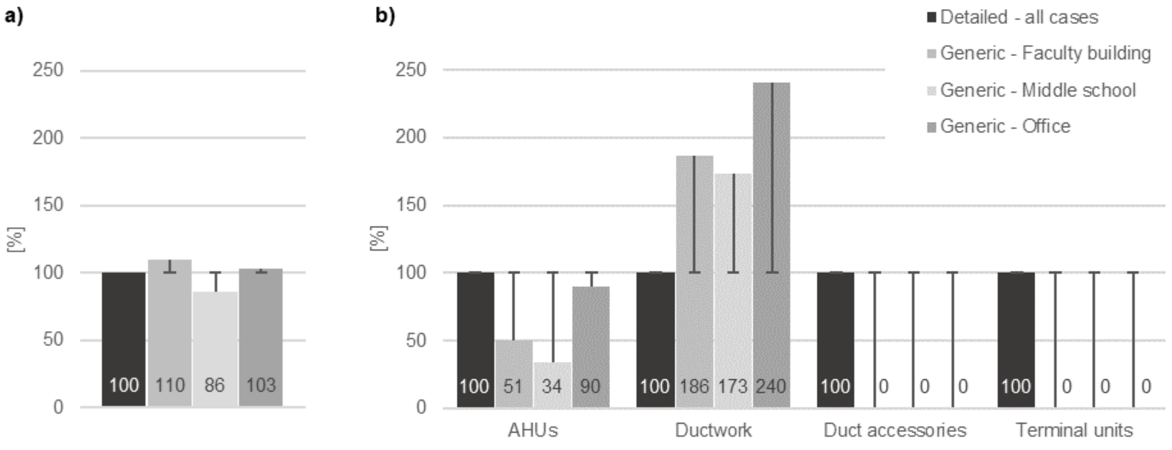

Figure 1. Weight comparison between generic assessment and detailed assessment **a)** for the whole ventilation system, **b)** for ventilation component categories

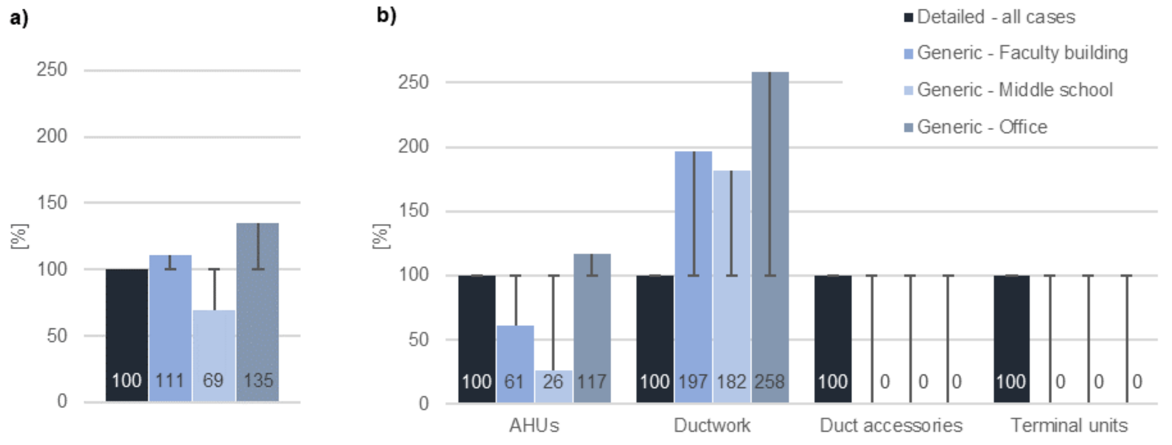

Figure 2. GWP comparison between generic assessment and detailed assessment **a)** for the whole ventilation system, **b)** for ventilation component categories

4.2. Detailed assessment

The results from the detailed calculations are presented with the use of the defined functional unit (m^3/h per m^2 heated floor area). The aim is to enable easy application of the obtained results in any building of the investigated category, with the use of the total heated floor area and the total air flow of the building.

Evaluating the average accumulated weight of the system (9278 kg per $m^3/h\ m^2$), the AHUs are the major contributor for all the investigated cases that account for 48% of the total weight in average (4456 kg per $m^3/h\ m^2$). It is followed by the weight of the ductwork with 37% (3434 kg per $m^3/h\ m^2$). The total share of duct accessories and terminal units is relatively small, amounting to 15% in total (1110 kg per $m^3/h\ m^2$ and 279 kg per $m^3/h\ m^2$ respectively). (Figure 3)

Considering the average GWP impact of the system calculated at 3.36E+04 kg CO_2 eq. per $m^3/h\ m^2$, the 48% share in weight from the AHUs translates to 60% (2.01E+04 kg CO_2 eq. per $m^3/h\ m^2$) of the total GWP, while the 37% share in total weight from the ductwork results only in 31% (1.04E+04 kg CO_2 eq. per $m^3/h\ m^2$) of the total GWP of the ventilation system. The relatively small weight of the duct accessories and terminal units (15%) translates to even smaller share of the total GWP accounting for 9% (1.97E+03 kg CO_2 eq. per $m^3/h\ m^2$ and 1.05E+03 kg CO_2 eq. per $m^3/h\ m^2$ respectively). (Figure 4)

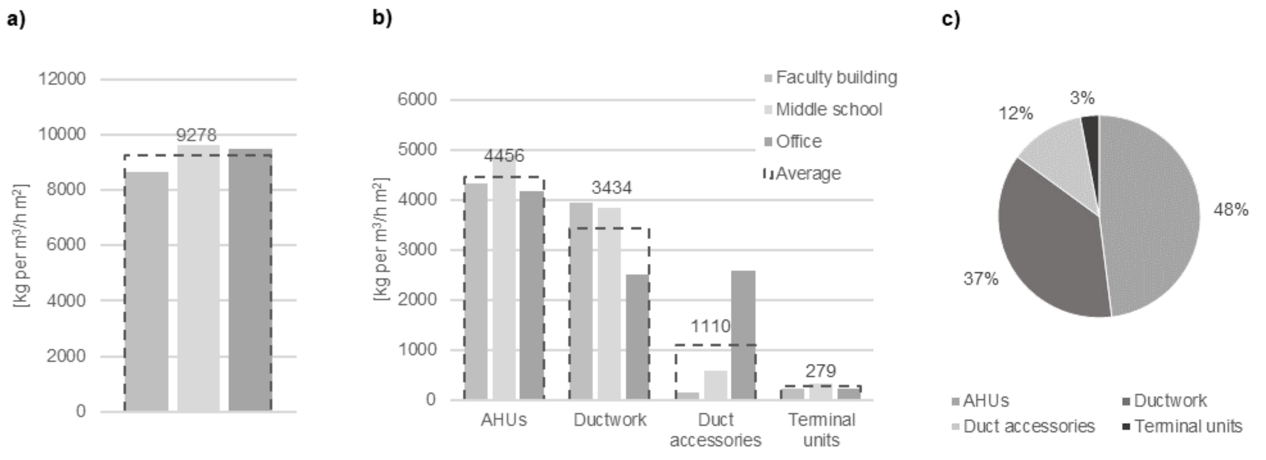

Figure 3. Average accumulated weight over the reference study period **a)** of the whole ventilation system, **b)** of ventilation component categories. **c)** Average share of the weight for different component categories

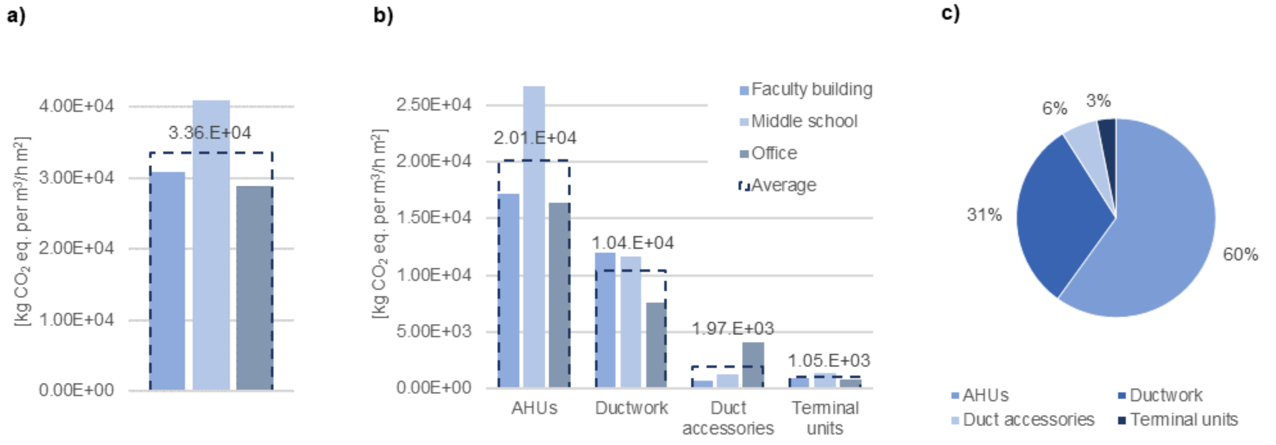

Figure 4. Average GWP over the reference study period **a)** of the whole ventilation system, **b)** of ventilation component categories. **c)** Average share of the GWP for different component categories

Because the AHUs have been determined as the highest contributor to the total GWP of the ventilation system, further analysis has been carried out, where all the different AHU components have been investigated separately for all the case-buildings.

The results show that the filters have the highest impact in regard to the total GWP, 40% (7.93E+03 kg CO_2 eq. per $m^3/h\ m^2$), corresponding to the highest share in the accumulated weight, 51% (2258 kg per $m^3/h\ m^2$), of the AHUs in average.

The component with the second highest GWP is the heat exchanger, with 30% (6.11E+03 kg CO_2 eq. per $m^3/h\ m^2$) of the total, even though the weight of the component and its share is relatively small (8%, 614 kg CO_2 eq. per m^3/h m^2).

The third and fourth largest contributor to the total GWP are the heating/cooling coils and the frame/casing of the unit, with 14% (2.86E+03 kg CO_2 eq. per m^3/h m^2) and 12% (2.36E+03 kg CO_2 eq. per m^3/h m^2) respectively. Even though the environmental impact of the two components is very close, this does not reflect the difference in their weight, where the heating/cooling coils amount to only 8% (339 kg per m^3/h m^2) of the total weight and the frame/casing to 18% (814 kg per m^3/h m^2).

The components with the smallest impact on the total GWP of the unit are the fans and dampers, with only 2% each (4.02E+02 kg CO_2 eq. per m^3/h m^2 & 4.65E+02 kg CO_2 eq. per m^3/h m^2 respectively). In terms of weight, the fans have higher share of 8% (376 kg per m^3/h m^2), whereas the dampers contribute with only 1% (54 kg per m^3/h m^2). (Figure 5 & Figure 6)

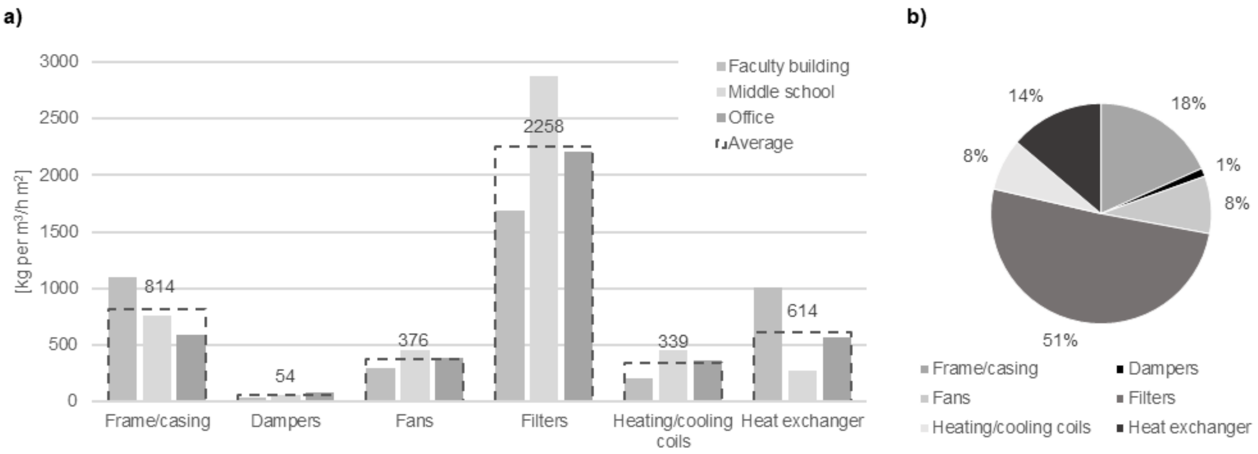

Figure 5. a) Average accumulated weight of the AHU components over the reference study period. **b)** Average share of the weight for different AHU components

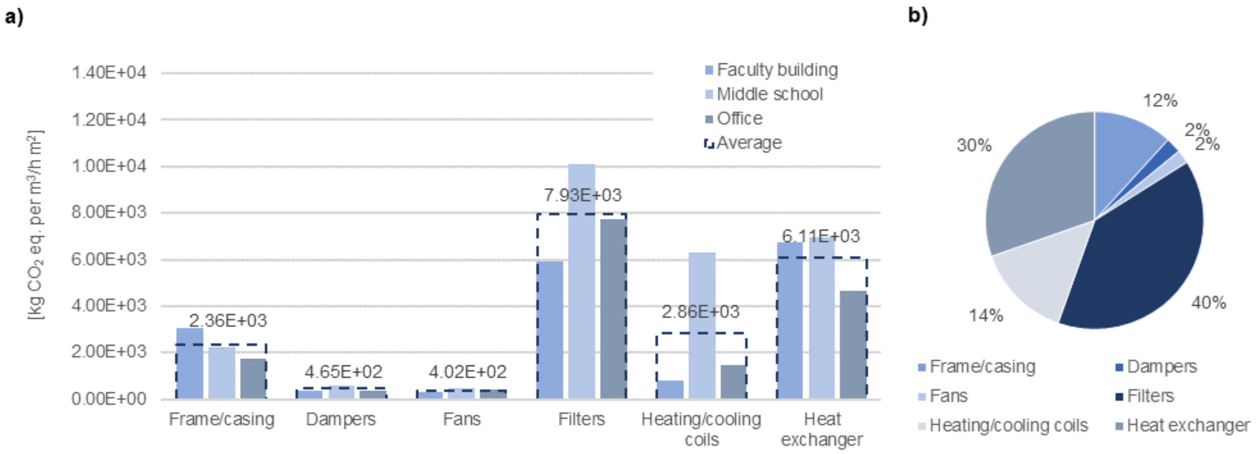

Figure 6. a) Average GWP of the AHU components over the reference study period. **b)** Average share of the GWP for different AHU components

The analysis of the different LCA stages shows that Production and Replacement are the two dominant contributors to the total GWP of the system, where the ductwork is dominant in the production stage as AHUs are dominant in the replacement stage, reflecting the shortened life-expectancy of their components. (Figure 7)

Supplementary result tables can be found in Appendix 1, Life Cycle Assessment – Average results for investigated building category.

Investigation into the general material composition and weight for each of the components in the ventilation system shows that galvanized steel and aluminium are the most used materials and therefore represent the highest contribution to the total GWP of the system. (Figure 7)

Assessing the different components of the ventilation system, the filters are not only the highest contributor to the total GWP of the AHU itself but also the second highest contributor to the total GWP of the whole system, amounting to 23.6%. The highest contributor among all the components (including the sub-components of AHUs) of the system is the ductwork with 31.1% share in the total GWP. Heat exchanger is coming in the third place, with 18.2%.

Considering the service-life of the investigated components in the ventilation system, the filters are the dominant player with 49 required replacements throughout the reference study period. (Figure 7)

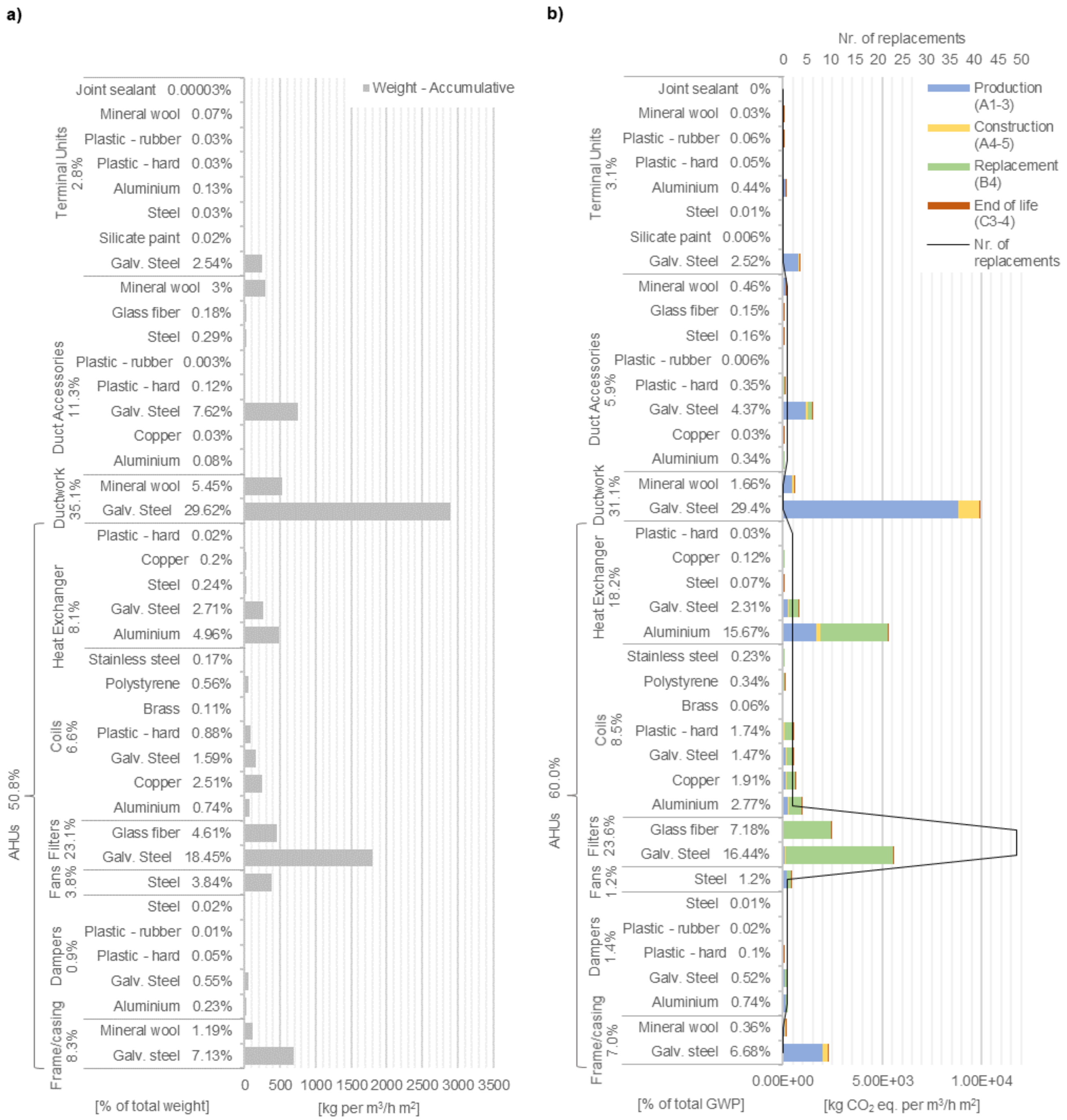

Figure 7. a) Average accumulated weight of ventilation components over the reference study period on system, component & material level **b)** Average GWP, share of the different LCA stages and number of replacements of ventilation components over the reference study period on system, component & material level

4.3. Optimisation potential on component level

Based on the results from Section 4.2 the components identified as the most critical ones are examined in their environmental impact improvement potential. The different available options for the components are evaluated in regard to their GWP, while keeping in mind their functional and technical requirements. Additional theoretical background on carbon reduction strategies in ventilation can be found in Appendix 1, Optimisation potential on component level.

The ventilation system component with the highest share of GWP is determined to be the AHUs, with 60% of the total impact from the whole system. Any reduction in its impact can therefore have significant improvement on the assessment. Further investigation singles out the heat exchanger and the filters as the AHU components with the highest contribution.

4.3.1. Heat exchangers

As the heat exchanger has been identified as one of the two main contributors to the total GWP of the AHUs, the different heat exchanger types that can be used have been investigated.

The calculation has been carried out using LCAbyg and data from Systemair for one AHU type for a specific air flow through the heat exchanger. The heat exchanger type has been changed for each calculation in order to examine how the total weight and GWP changes. The service life for all the investigated types is identical. The input data and the results of the calculations can be found in Appendix 1, Optimisation potential on component level, Heat exchangers.

The results of the assessment show that the rotary heat exchanger has the lowest GWP, reflecting its weight. The run-around coil coming in second place in regard to the GWP, despite its weight. The GWP of the plate heat exchangers (both cross- and counter-flow) turns out to be almost two times higher compared to the rotary heat exchanger, where the counter-flow heat exchanger results in slightly better GWP compared to cross-flow heat exchanger.

Besides the environmental profile of the different heat exchanger types, other parameters need to be taken into consideration as well, when selecting the most suitable to be used in a project. These criteria include for example the efficiency of heat recovery [24] and risk of leakage [25]. (Table 1)

Table 1. Heat exchanger types – Optimisation potential

Heat exchanger type	Heat recovery efficiency	Risk of leakage	Weight	GWP
Rotary	<85%	moderate	44%	37%
Cross-flow	<85%	low	98%	100%
Counter-flow	<90%	low	100%	99%
Run-around coil	<70%	none	95%	41%

4.3.2. Filters

Another main contributor to the total GWP of an AHU is the filters due to the requirement of their replacement minimum once every year [26]. This is to ensure that hygienic and comfort requirements for dust and other particles are fulfilled as well as to ensure the performance and service life of all the other components in the system. [27]

Since the frequent replacement of the filters is essential, the most impactful action how to reduce the carbon emissions related to filters is through the energy used under operation of the building. The operational stage is however outside of the scope of this project and will not be investigated further.

4.3.3. Ductwork

The ductwork has been identified as the second highest contributor, among the component categories, to the total GWP of the ventilation system, with 31% share. Parameters that affect its environmental impact and show possibilities for improvement are the shape of the ducts, the layout of the distribution system and the materials it is made of.

The conventionally used shapes for the ductwork are round ducts and rectangular ducts, where each shape has its own applications.

Round ducts have for a given cross-sectional area the smallest circumference compared to the perimeter of the rectangular ducts (or any other shape) of the same cross-sectional area. This results in significant saving in material consumption. At the same time, the round ducts have the smallest pressure loss per m for a given cross-sectional area, resulting in higher efficiency in transporting the air. It is therefore recommended to use rectangular ducts only where the space for the installations is limited or in other special circumstances, as is a common practice. [28]

Regarding the design/layout of the distribution system, any unnecessary pressure losses should be avoided and the pathways should be as short as possible so as to decrease the performance requirements for the AHU and its components sizes (material quantities used) as well as the material quantities for the distribution system itself. [28]

The most common material used for ventilation ducts is sheets of metal. Typically, they are made of galvanised steel, but other metals, such as aluminium, can be used as well under certain circumstances.

There are also non-metallic ducts available in the market. One of the options is Fiberglass Reinforced Plastic (FRP), which is mainly used for chemical exhaust or exhaust for corrosive media (air mixtures with vapours, dust and/or reactive gasses). [29]

Another non-metallic option, that is applicable for the investigated building type, is fabric ducting made of polyester. These ducts have been successfully used in schools, offices and other similar types of buildings. Compared to their traditional sheet metal counterpart, they have in addition to the environmental advantages (Table 3) also technical, hygienic and economic advantages (Table 2). The fabric ducts can be used as ducting for both air supply and exhaust (air transfer in branches, connection ducts and bends of the distribution system) as well as air diffusion into the rooms (terminal units). The pressure losses of fabric ducting are comparable to the metal sheet ducts. [30] [31]

The calculation has been carried out using LCAbyg and the duct quantities have been taken from a random section of one of the case-buildings. The input data and the results of the calculations can be found in Appendix 1, Optimisation potential on component level, Ductwork.

The results of the assessment show that the fabric ductwork has significantly lower GWP compared to the galvanised steel option, reflecting its weight, even with considering the shorter service life and the need for replacement.

Table 2. Galvanised steel vs. fabric ducts – technical properties

Duct material	Condensation risk	Weight	Cost	Installation time	Easy cleaning	Sound attenuation
Galv. steel	yes	high	high	long	no	no
Fabric	no	low	low	short	yes	yes

Table 3. Galvanised steel vs. fabric ducts – environmental properties [per m^2 surface area]

Duct type	Service life	Weight	GWP
Galvanised steel	>50 years	100%	100%
Fabric	25 years	7%	19%

5. Discussion

In line with the findings of previous studies [11] [15], there is a general problem with data availability and quality when assessing the environmental impact of building materials, especially in connection to technical installations [3]. The process of assessing the cases as well as the results obtained underline this issue.

Under the generic assessment, the total absence of certain ventilation component categories (duct accessories, terminal units) has been observed, as well as the lack in variety of the available remaining component categories (AHUs, ductwork).

Under the detailed assessment, the technical data on the investigated systems was found lacking in some areas. Example of this is the difference between the specific cases in relation to ductwork and duct accessories (Figure 4), where the office model contains more silencers (duct accessories) compared to the other two buildings, even though they have the same requirements for attenuation of sound from technical installations [2]. The increased number of silencers in the office building results in notable reduction in ductwork compared with the other cases. The difference in results is therefore associated with incomplete information in the BIM models. The incomplete environmental data available, resulting in necessary assumptions on certain products, also affected the accuracy of the results.

As the comparison between the generic and detailed assessment implies (Figure 2) the deviation in the results between the two is apparent, especially on the component level. This combined with the absence of duct accessories and terminal units from the generic assessment calculation point to unreliability of the generic assessment.

The combination of the lack of information available on environmental impact of the HVAC systems as pointed out in [3] and the unreliability of the assessment of ventilation systems based on the available generic data as this paper presents, shows a need for reliable reference values to be established. The values presented in this paper could possibly be used as such reference values for the educational and office building category. Presenting the results in functional unit of kg CO_2 eq./m^3/h m^2 makes them applicable for other cases under the same category. (Table 4)

Table 4. GWP reference values

	GWP [kg CO_2 eq. per m^3/h m^2]
Ventilation system	**3.36E+04**
Distribution system	1.34E+04
Terminal units	*1.05E+03*
Duct accessories	*1.97E+03*
Ductwork	*1.04E+04*
AHUs	2.01E+04
Heat exchanger	*6.11E+03*
Heating/cooling coils	*2.86E+03*
Filters	*7.93E+03*
Fans	*4.02E+02*
Dampers	*4.65E+02*
Frame/casing	*2.36E+03*

The obtained results indicate that on system level the AHUs are the main contributor to the total GWP, followed by the ductwork. On the component level within the AHU the filters are shown to have the most impact on the GWP, where the heat exchanger is coming in second place. The cause of this, as demonstrated in the results section 4, is the weight of the components, their material composition and their service-life in relation to the reference study period. The investigation in terms of material composition of the component categories highlights the galvanised steel as the most used material and aluminium as the most impactful per its weight. (Figure 7)

The difference between the GWP of the specific cases related to the AHUs (Figure 4) is caused by the use of a variety of different component types and their quantities. For example, the Middle school case-building uses heat pump as an alternative to cooling coil. (Figure 6) While heat pump saves energy consumption under operation, its embodied carbon is significantly higher compared to the traditional cooling coils used in AHUs.

The presented findings in this study set the foundation for possible carbon reduction options, where the critical areas of the system have been determined and their potential for optimisation has been investigated. Under the AHUs category, the rotary heat exchanger has the lowest GWP, followed by the run-around coil heat exchanger, while the plate heat exchangers have the highest GWP. The results are a reflection of the components weight and material composition, since the life-expectancy is the same for all the types. It is recommended however, to take into consideration also other technical and performance parameters, such as risk of leakage and/or heat recovery efficiency, as well as the specific needs of the project when deciding on the type to be used. (Table 1)

The filters, even though being one of the critical components in the system, do not show much of an optimisation possibilities in terms of embodied carbon, since there is a requirement for them to be replaced once a year for hygienic, technical and comfort purposes. As of date, maintenance options and/or partial reuse of the component is not a standard practice in the industry. Recycling strategies, partial replacement of only the medium or other maintenance possibilities to extend the service-life of the component should be developed and introduced to the industry.

The ductwork, another critical component category in terms of its environmental impact, shows potential for carbon reduction in different areas, such as the shape of the ducts, the layout of the distribution system or the materials used for production of the components. The use of circular ducting where possible, optimal layout with short pathways and minimal pressure losses can all result in decrease of material use and therefore positively affect the environmental impact of the system. In terms of the material, the results point to fabric ducting as an alternative to the traditional galvanised steel that can result in significant carbon reduction. (Table 3)

Other than the carbon reduction, there are also other technical properties of fabric ducting that should be considered during the decision-making process. (Table 2)

The obtained reference value on system level (3.36E+04 kg CO_2 eq. per m^3/h m^2) converted to a unit of kg CO_2 eq. m^2/year (0.76 kg CO_2 eq. m^2/year), compared to the threshold limits set in The voluntary sustainability standard [1] of 12 kg CO_2 eq./m^2/year for year 2023, takes a 6.4% share of the total acceptable carbon emissions for buildings bigger than 1000 m^2. The share increases to 10.2% for a threshold limit of 7.5 kg CO_2 eq./m^2/year set for year 2029. (Appendix 1, Carbon emission threshold limits) Considering that the calculated value of 0.76 kg CO_2 eq. m^2/year includes only the embodied carbon of the ventilation system, the results suggest that optimisation is essential in this area in order to fulfil the set threshold limits for the whole building.

The results of this study (0.76 kg CO_2 eq. m^2/year) are in line with the result of study [16], where the embodied carbon of an investigated VAV ventilation system in an office building under comparable boundary conditions was calculated at 0.69 kg CO_2 eq. m^2/year. Although there is other research on this topic, none of it focuses on the ventilation systems specifically (focus is on HVAC systems in general), or on the building category of educational and office buildings, with varying boundary conditions, making the results incomparable with this study. Thus, more research focused on the HVAC systems not as a whole but as separate entities is recommended. The research area should cover all the different building categories (with sufficient number of case-buildings in each category) with respect of their specific requirements.

6. Conclusion

The focus of this study is the embodied carbon of the ventilation systems in educational and office buildings. The environmental assessment has been done on three different case-buildings using the LCAbyg tool.

The comparison between the generic and detailed assessment for each of the case buildings point to the generic assessment results to be insufficient.

The results from the detailed assessment are therefore used as a basis for setting up new reference values for the investigated building category. The reference value set consists of generalized GWP values in kg CO_2 eq. per m^3/h m^2 for the system as a whole as well as for each specific component category. The results of the detailed assessment highlight the AHUs, specifically the filters and heat exchanger, as one of the critical components of the system in regard to GWP, together with the ductwork.

The critical components have been investigated in relation to their potential for carbon reduction, where the rotary heat exchanger has likely the lowest GWP out of the different types available. Regarding the ductwork, the use of fabric ducting presents significant potential in reducing the environmental impact of the air distribution system. Since there is a requirement for the filters to be replaced every year, the possibilities for carbon reduction are very limited and unavailable in the market as of date. Therefore, it is recommended to research this area further.

The consistent lack of product specific environmental data related to ventilation systems presents an issue in this study and in general. Thus, it is essential that the initiative to fill in these gaps in available data continues across the market.

The comparison of the results in this study with the upcoming threshold limits for carbon emissions point to the importance of further research on HVAC systems in relation to embodied carbon and its reduction strategies.

Acknowledgements

The authors of this paper would like to thank MT Højgaard A/S for the collaboration on this study by providing necessary data on the case-buildings included in the research.

Additionally, thanks are also due to the representatives from Hoval A/S, Prihoda s.r.o. and tt coil A/S for providing assistance with selected inventory data.

Appreciation also goes to the supervisors for this study, Leonora Charlotte Malabi Eberhardt, Kai Kanafani and Rasmus Lund Jensen for their guidance throughout the whole process.

Supplementary data

Appendix 1 – supplementary description of the process, calculations and results (report structure)

Appendix 2 – lists of components, their materials composition and quantities, product datasheets & EPDs, LCAbyg raw data and results

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