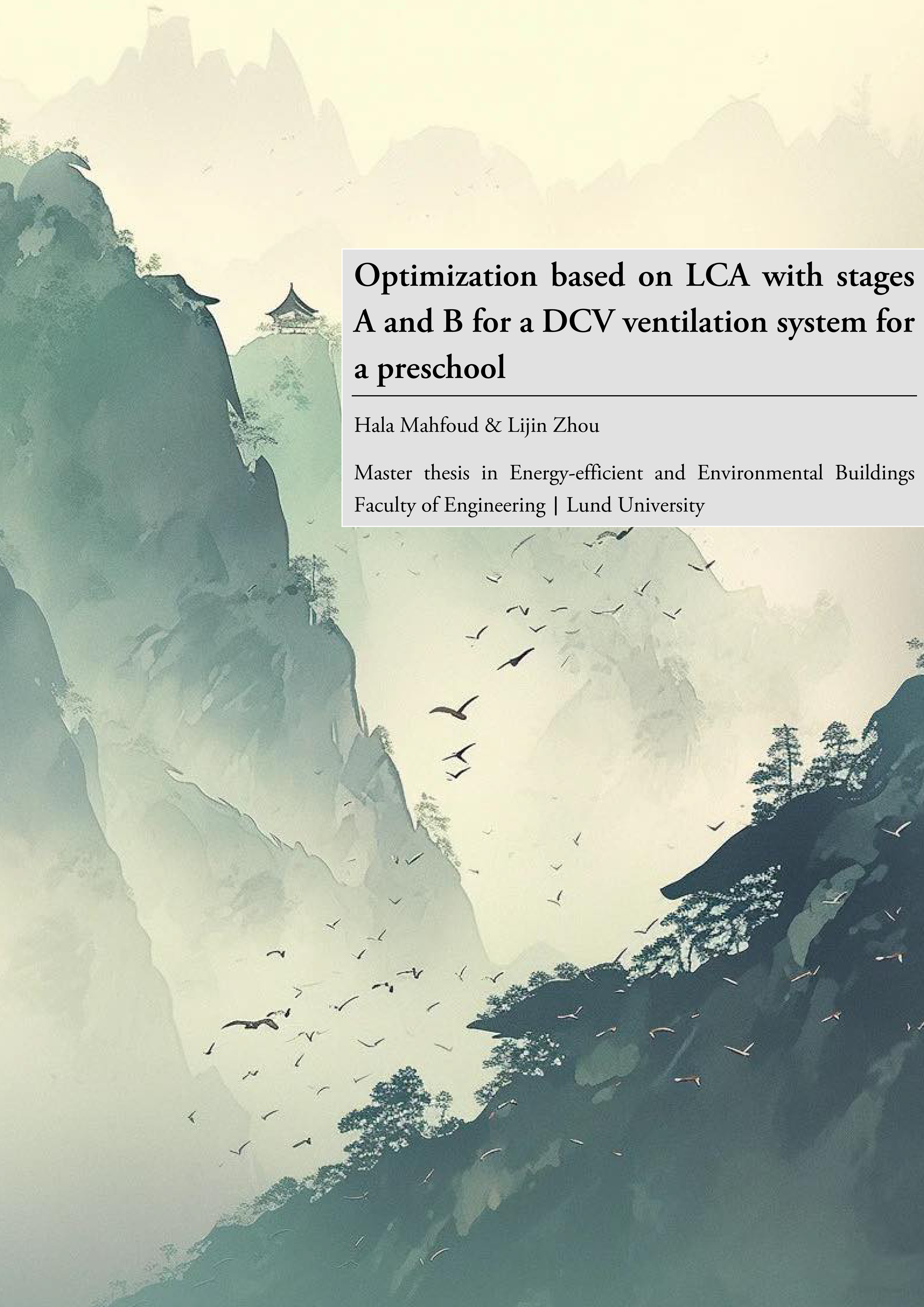

Optimization based on LCA with stages A and B for a DCV ventilation system for a preschool

Hala Mahfoud & Lijin Zhou

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

Lund University

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

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This international program provides knowledge, skills and competencies within the area of energy-efficient and environmental building design in cold climates. The goal is to train highly skilled professionals, who will significantly contribute to and influence the design, building or renovation of energy-efficient buildings, taking into consideration the architecture and environment, the inhabitants' behavior and needs, their health and comfort as well as the overall economy.

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

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Abstract

In pursuit of sustainable development within the building industry, there is a shift towards design strategies that are energy efficient and environmentally friendly. The European Commission has a goal of becoming climate-neutral by 2050 and the United Nations has also developed Agenda 2030 to aid in the reduction of the environmental impact. The city of Malmö has also developed a local plan for achieving a climate-neutral construction and infrastructure sector in Malmo by 2030 – LFM30.

The ventilation system accounts for a significant percentage of the environmental impact caused by a building. With previous studies placing weight on individual stages of a life cycle of the ventilation system being either the production and construction stage A or the use stage B, this study aims to investigate the combination of these stages by evaluating different design strategies while considering the economic factor. Evaluating the performance of the implemented strategies was achieved through conducting a comprehensive analysis involving Life Cycle Assessment (LCA), Life Cycle Cost (LCC), and an integrated life cycle assessment (ILCA), following LFM30:s guidelines and climate staircase. LFM30:s climate staircase includes the traditional level representing the base case, the Base level includes improvements without additional costs, BATNEEC involves efficient measures with a reasonable cost increase, and BAT approach where cost is flexible allowing for multiple measures. The potential environmental impact category taken into consideration for the LCA was the Global Warming Potential (GWP) measured in kg CO_2 equivalents.

Two preschools in Sweden based on a standard model being constructed in different cities were used as a case study to determine the environmental impact of their current ventilation systems and the potential design strategies implemented. The ventilation system in these preschools consisted of two air handling units, LA01 supplying airflow to the whole building and LA02 only designated for the kitchen area which is a special trait in this project. The design strategies implemented in this study were a Demand Control Ventilation system (DCV) system for the BATNEEC approach and the use of recycled steel for the duct system for the BAT approach in addition to the DCV system, with the Base level considered a limitation. For the installation of a DCV system, a ventilation schedule with a reduced designed airflow volume was created based on the occupancy level provided by interviews and measurements conducted. The study findings indicate that a Demand Control Ventilation system regulated with carbon dioxide sensors could lower the designed airflow volume to 80%-65%.

Considering the special trait related to these preschools, system LA02 has a higher kg CO_2e emission per m^2 gross floor area (GFA) while having a lower amount in total kg CO_2e emission compared to system LA01. The AHU accounts for the largest percentage of the total environmental impact of the ventilation system with the duct system accounting for the second largest. The study shows potential in placing weight on both the construction and production and the use stages of a project. The results indicate that measures related to installed material choice such as the use of recycled material have mainly a direct impact on stage A and not B while measures related to energy efficiency have a direct impact on stage B without affecting stage A negatively. The implementation of a Demand Control Ventilation system reduced the energy demand by 55% and thus the environmental impact due to Global Warming Potential impact (GWP) by 55%-67%. The implementation of any of these measures had a higher investment cost for installed material but made savings in considering the cost of the operational energy use. It was also concluded that the best-performing case could vary depending on results from the ILCA with whether a greater weight was placed on LCA or LCC.

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Abbreviations

Boverket	The Swedish National Board of Housing, Building and Planning
CO_2e	Carbon Dioxide Equivalent
GWP	Global Warming potential
GHG	Greenhouse gases
LCA	Life Cyle Assessment
LCC	Life Cyle Costing
ILCA	Integrated Life Cycle Analysis
CAV	Constant air volume
DCV	Demand control ventilation
HVAC	Heating, Ventilation, and Air conditioning
BATNEEC	Best Available Technology Not Entailing Excessive cost
BAT	Best Available Technology
LFM30	Local roadmap for a climate neutral building sector in Malmo 2030

Table of Contents

1 Introduction

1.1 Background

In the building sector, the shift towards a higher degree of sustainable development is significantly required yet also presented with major challenges. Sustainable development is defined as the development that meets the present needs without compromising the future possibility and ability to meet those needs and requirements. A complete assessment of sustainable development includes the social, environmental, and economic aspects. (KTH, 2021) The environmental aspect is connected to the ecosystem, where a sustainable consumption of raw materials should be applied. Social sustainability prioritizes human well-being and rights while economic sustainability aims to achieve economic growth and stability without negatively affecting the environmental and social aspects. (Public & science Sweden, 2023)

To balance these three aspects related to sustainable development, several organizations and initiatives have set goals and developed guidelines. The United Nations developed Agenda 2030 and set 17 Sustainable Development Goals with Goal 11: Sustainable cities and communities, aiming to reduce the environmental impact of cities through sustainable building. The European Commission aims for net zero emissions by 2050 (European Commission, u.d.). In Sweden, the construction and real estate sectors account for a significant percentage of the resulting environmental impact, being almost 22% of Sweden's total greenhouse gas emissions in 2020 (Boverket, 2024). In 2018, the construction and infrastructure sector in Sweden developed a plan to achieve climate neutrality by 2045, aiming for net-zero emissions of greenhouse gases. The city of Malmo signed the national plan for 2045 to become the first in Sweden to endorse the 'Declaration of Cities Commitment to the 2030 Sustainable Development Agenda'. From this, a local plan emerged for achieving a climate-neutral construction and infrastructure sector in Malmo by 2030 - LFM30. (LFM30, u.d.)

Commercial and residential buildings fraction is up to 40% of the total energy use in developed countries, a phenomenon intensified by rising demand for building services and thermal comfort. Approximately 50% of building energy usage is designated to the process of heating, ventilation, and air conditioning (HVAC). (Borja-Conde, Nadales, Ordonez, Fele, & Limon, 2024) Occupants spend most of their time indoors especially in extreme climates such as in Sweden creating a higher demand for satisfactory indoor conditions, adding to the energy use designated to the HVAC system. Different buildings have variations in ventilation requirements based on the function and activities performed indoors. In preschools, the main occupant group is children who are more sensitive to the conditions of the indoor climate increasing the need for good ventilation. (Abel & Elmroth, 2012)

The environmental impact caused by the life cycle of a ventilation system can be mainly linked to the production and operational phases. The Production stage implies installed material while the operational includes energy use. The percentage that these stages account for can vary depending on design and operation system type and can therefore be optimized for a good performance in both stages without undermining the function of a ventilation system. (Schlanbuscha, o.a., 2016)

1.2 Aim and Objective

This study aims to find approaches to evaluate the system based on both life cycle stages production and operation of a ventilation system in preschools while maintaining ventilation requirements and a good indoor climate. The objective is to evaluate parameters such as the environmental impact and economical aspect by conducting an LCA and LCC calculation and weighting their importance through an ILCA analysis.

1.3 Research questions

The main research questions of this study are the following:

- How to optimize the system regarding the construction and operational phase of the ventilation system considering the GWP environmental impact in kg CO_2e / through a life cycle analysis and cost through a life cycle cost analysis?
- How can the results be utilized in an action plan to help reach goals set by LFM30 regarding energy efficiency and environmental buildings?

A secondary research question considered is:

- What is the potential of implementing the investigated design strategies in renovation projects?

1.4 Limitations

The study conducted was limited within Sweden where only the ventilation part of the HVAC was analysed. A building's losses consist of transmission loss though the envelope, leakage and ventilation loss but since the building envelope was not modified in this study, it is therefore considered to be a controlled variable keeping the transmission and leakage losses through it unchangeable. Therefore, the only uncontrolled variable factor for energy use was due to the ventilation system. When it comes to LCA, the functional unit was set to be a ventilation system for preschool presented per m^2 and the system boundaries for the LCA were A1-A5 stages production and construction and B2 maintenance, B4 replacement, and B6 operational energy use were the only modules considered within the use stage B. Only one environmental impact is chosen being Global Potential Warming (GWP). Only two out of three dimensions are going to be considered for sustainable development being environmental and economic development, excluding the social aspect. Within the LFM30 climate staircase implemented, the Base level was not included in the study with the focus directed towards the BATNEEC and BAT approach. Occupant behaviour such as opening windows to manually ventilate was not considered, however, it was observed that it can affect the energy use of the ventilation system. A detailed thermal comfort and moisture analysis was not considered.

2 Theory

2.1 Indoor climate

In Sweden, people spend around 90% of their time in indoor spaces, be it at home, school, or work making it of great importance that buildings have a good and healthy indoor climate (Boverket, 2022). Indoor Air Quality (IAQ), thermal environment, lighting, and acoustics make up the indoor climate and are an indication of the comfort level inside the building. Indoor air quality, thermal factors, and acoustics are to a huge extent directly connected to the design of a ventilation system. (Warfvinge & Dahlblom, 2010)

IAQ is directly related to the health and productivity of the occupants. Factors that may affect IAQ are temperature, humidity, carbon dioxide (CO_2) level, airflow rate, and pressure (Selamat, o.a., 2020). Providing a satisfactory IAQ for occupants can be achieved with the help of ventilation control systems. Set points are usually considered in ventilation control strategies for the parameters affecting the indoor climate. Set points for CO_2 concentration level are the most common for IAQ control in buildings because it is an occupant-related pollutant and the easiest to measure. (Chenari, Carrilho, & Manuel, 2016) The air is considered bad when the CO_2 concentration is above 1000 ppm, but 20,000 ppm is the limit where the effect on health occurs. There are therefore minimum requirements set by Boverket for air change rate to ensure the level of oxygen needed being 0.35 l/s per m^2 and 7 l/s per person. (Warfvinge & Dahlblom, 2010)

Thermal comfort is a subjective perceived satisfaction with the thermal environment. Similar parameters to the ones that affect the IAQ, influence how the thermal environment is experienced being the temperature of air and surrounding surfaces, the velocity of airflow, and the humidity of air. It is almost impossible to create a thermal environment that is satisfactory to all occupants due to two factors that are individual-dependent being activity level and clothing. (Selamat, o.a., 2020) To reach a satisfactory level of thermal comfort, air must be supplied at an optimal temperature and therefore energy is required to heat or cool the air based on the demand to a comfortable level. There are certain thresholds for the indoor environment parameters to ensure thermal comfort. The operative temperature being the temperature of the air and surrounding surfaces, should be between 20 to 25°C. Inconvenience is experienced when the average air velocity is above 0.15 m/s. (Warfvinge & Dahlblom, 2010)

Unwanted sounds regardless of the level, tone, and intensity are considered noise and can affect the performance and health of the occupants. There are general guideline values that should be followed when assessing sound levels in a building, where the equivalent sound level should not exceed a value of 30 dB. (Folkhälsomyndighetens, 2014) Upon design, it is also worth considering that noise can be Internally generated by the ventilation installations from the fan in the AHU and air moving through ducts and supply and exhaust air devices. (Warfvinge & Dahlblom, 2010) When having a mechanical ventilation system it is recommended that the air velocity from a supply diffuser should not exceed 0.2 m/s. Recommended and maximum accepted velocity values in the duct system related to sound levels for schools are presented in Table 1, below. (Arora, 2010)

Table 1. Recommended and maximum accepted air velocity in ducts.

Designation	Recommended velocities /(m/s)	Maximum velocities /(m/s)
Main ducts	3.4 - 4.6	5.6 - 8.0
Branch ducts	3.0	4.0 - 6.0
Branch risers	2.5	4.0 - 6.0

2.2 Ventilation system

Every residence needs a ventilation system to comply with air quality and indoor climate standards. The ventilation system plays an important role in eliminating pollutants and harmful substances from indoor air and neglecting ventilation can result in moisture and mould problems, posing health risks. (Boverket, 2024) Hence the main function of a ventilation system is to provide fresh air by supplying the minimum required air changes to maintain good air quality in the areas frequently occupied and remove polluted air from the kitchen, bathroom, and hallway. The minimum requirement regarding the ventilation flow is 0.35 l/s per m^2 area, in addition to 7 l/s per person if it is a local building and with a normal room height of 2.4 meters according to Boverket. (Folkhälsomyndigheten, 2023) Based on the needs of the building another function of the ventilation system can be to heat and cool the space or only the air provided to a comfortable level (Warfvinge & Dahlblom, 2010).

2.2.1 Life cycle impact assessment (LCIA)

The LCIA has the aim to create an understanding and evaluation of the significance and magnitude of the potential environmental impact of the system under investigation. In this phase, the relevant impact categories chosen for analysis go through the process of classification, characterization, normalization, and weighting. The classification process consists of assigning the elementary flows to the relevant environmental impact categories. In the characterization process, the elementary flows are multiplied by a characterization factor representing the unit of the environmental impact category. (Hassan, 2019) Normalization implies expressing the potential environmental impact categories relative to a reference while weighting implies relative evaluation of their significance aligned with the goal of the study (Nieuwlaar, 2013). Quantification of the environmental impact indicators is mandatory, however, subsequent normalization and weighting are optional according to the ISO standard. The final phase being interpretation aims to evaluate the outcome from previous stages to deduce a conclusion and suggest recommendations. (Finnveden & Potting, 2014)

2.2.2 Types of ventilation system

There are different types of ventilation systems which can be divided into three categories: Natural ventilation, mechanical ventilation, and hybrid ventilation. Natural ventilation is driven by natural forces such as thermal buoyancy, caused by differences in air density due to outdoor and indoor temperature differences (Svensk ventilation, u.d.). This system is simple and requires no fans, resulting in zero energy demand but can cause pressure differences, uneven air distribution, and temperature variations on different floors. Mechanical ventilation is most common and is driven by fans and has therefore an energy use, however dependent on the functionality. Mechanical ventilation can help create a negative pressure within the building to prevent moisture problems. (Warfvinge & Dahlblom, 2010)

There are different types of mechanical ventilation systems which are supply-only, exhaust-only, and balanced ventilation including supply and exhaust with or without heat recovery. Hybrid ventilation is a combination of natural and mechanical ventilation to optimize the system and reach a low energy demand but is possible to apply in countries with moderate weather conditions. Therefore, considering the extreme weather conditions in Sweden balanced mechanical ventilation has become the normal application in buildings. (Svensk ventilation, u.d.) A ventilation system consists of four subsystems divided into a room system, distribution system, Air handling unit (AHU) system, and control system. The room system includes supply and exhaust air devices and the distribution system includes ventilation ducts. The Air handling unit (AHU) is a composition of different components based on need such as a fan, silencer, damper, filter, heat exchanger, cooling, and heating coil. The control system regulates the temperature, pressure, and airflow. The composition and type of the ventilation system chosen depends on various factors such as the requirements for indoor climate and air quality by users and the requirements in terms of investment costs, operating costs, space requirements, and maintenance by the client. (Warfvinge & Dahlblom, 2010)

2.2.3 Airflow supply methods

Mechanical ventilation systems utilize two principles for air distribution within occupied spaces: displacement and mixing ventilation. Displacement ventilation involves supplying air at low velocity and temperature near the floor, where the air distribution is driven by room heat sources, see Figure 1. This air spreads across the floor, displacing warm, polluted air, which rises to the ceiling due to convection. However, caution is needed when placing the diffusers to avoid drafts and the space close to the diffusers must be free from obstacles. (Lindab, 2018)

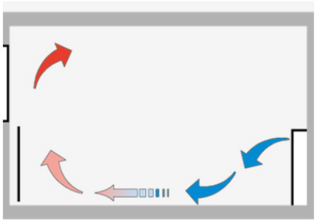


Figure 1. Displacement ventilation (Taken from Swegon).

Mixing ventilation involves supplying air at a high velocity from normal roof or wall diffusers, see Figure 2, allowing mixing with the room air and even air distribution in all parts of the room. This ensures small temperature variations and consistent pollutant concentration across the room, maintaining thermal comfort. However, an increase in velocity increases sound levels, which affects the diffusers requirements for maintaining a low sound level, and depending on the desired supply air temperature, it's important to adjust the velocity accordingly. (Lindab, 2018)

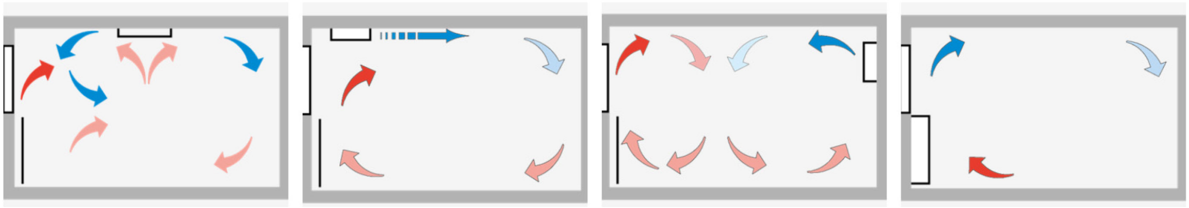


Figure 2. Mixing ventilation (Taken from Swegon).

The air in a diffuser can be dispersed in different ways, from 1-way dispersion up to 4-way dispersion. Positioning the diffuser in the centre of the roof will allow the air to stream down along the wall, reducing the risk of draught. It's important to note that caution should be taken when placing two diffusers too close together as this can result in air collision and increased draught risks. (Warfvinge & Dahlblom, 2010)

2.3 AHU components

2.3.1 Fan

A fan's primary role is to induce airflow within a space and this is achieved through rotating paddle wheels powered by an electric engine. This creates pressure differences between the two sides of the impeller, generating airflow. Various fan designs influence pressures and airflow, thus proper dimensioning is important to overcome pressure resistance in the duct system being one-time losses (dampers, diffusers, filters), and friction losses, which occur in the whole system due to the friction between the air and the walls of the duct. (Jernkontorets energibok, u.d.) Fans must be sized to provide pressure increases corresponding to total pressure drops in system components. There are three main types of fans and the differences are based on the direction of airflow through the impeller, radial fans, axial fans, and cross-flow fans. (Warfvinge & Dahlblom, 2010)

Radial fans, also known as centrifugal fans, utilize centrifugal force to generate pressure and increase velocity. This fan type features a blade wheel that rotates within a shell-shaped capsule. As the blades spin, air enters axially and is expelled radially due to centrifugal force, thus the inlet and outlet are perpendicular to each other. (Warfvinge & Dahlblom, 2010) Radial fans can be both forward and backward curved each impacting the fan's performance. Forward curved fans have high fan pressure, are cost-effective, require less space, and produce lower sound levels with an efficiency ranging from 55-65%. On the other hand, backward curved fans have lower fan pressure, are more expensive, and occupy more space but have a higher efficiency of around 75-85%. (Jernkontorets energibok, u.d.)

Axial fans, also known as propeller fans will move the air in the same direction as their spinning motion which makes them efficient for transporting large volumes of air with low resistance. They have an efficiency of 75%-85% and are preferable in applications where high-pressure airflow isn't necessary. Cross-flow, or tangential fans draw in air and distribute it evenly over a wide area, hence they are ideal for applications requiring gentle air circulation, like air conditioners and heaters. While they offer high flow rates and low sound levels, their efficiency is lower being around 30%-40%, due to blade impact losses. (Warfvinge & Dahlblom, 2010)

2.3.2 Fan and System Curve

The system and fan curves describe the variation in total pressure within the system at different airflows, hence they are important considerations when selecting a fan. Understanding these curves is essential for optimizing performance and efficiency and preventing over-sizing or under-sizing. (Aerovent, u.d.) A properly dimensioned fan reduces energy use, ensures the correct airflow in ducts for thermal comfort, and prolongs fan lifespan by avoiding overloading or underloading. Parameters that affect the choice of the fan are the fan curve, system curve, operating point, and brake horsepower (BHP). (Ecogate, u.d.)

The fan curve describes the operational performance of a fan and shows the relation between the flow through the fan and the static pressure it can overcome at various flow and pressure settings. Once the fan curve is established, the brake horsepower (BHP) can be determined which represents the minimum power required to operate the fan. (Ecogate, u.d.) The system curve illustrates how the required static pressure changes with varying flow rates and more airflow indicates a higher pressure drop. Each system has its own curve's characteristics depending on the design and installation location of the fan. (Aerovent, u.d.)

The point of intersection between the fan and the system curve is known as the system operating point which represents the fan's balanced performance within the system reaching equilibrium. (Aerovent, u.d.) It reflects the fan's effectiveness and during fan selection, a comparison of various fan curves with the system curve helps to identify the fan that best complements the system's needs. However, the actual operating point after installation may be slightly lower due to system errors, thus the fan's efficiency during installation often falls below the stated value. (Ecogate, u.d.). Figure 3, below illustrates the fan curve, system curve, and brake horsepower curve (BHP).

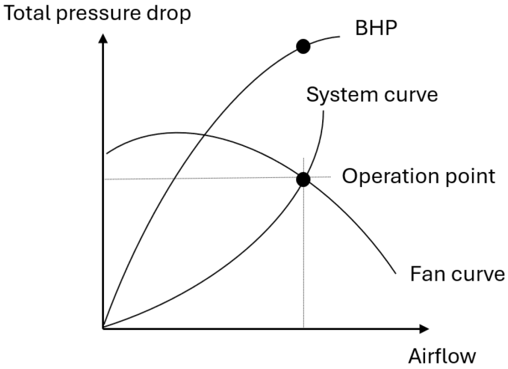


Figure 3. Illustration of System and Fan Curve (Inspired by Aerovent).

Finding an ideal fan for the chosen system may not always be possible. There are therefore two approaches to adapting it. Adjusting the number of revolutions (RPM) will shift the operation point along the system curve and while altering the damper it will change both the system curve and the operation point along the fan curve. Additionally, a dirty filter can shift the system curve, therefore it's important to clean and maintain the filter, (Warfvinge & Dahlblom, 2010).

2.3.3 Specific Fan Power (SFP)

SFP stands for Specific Fan Power and serves as a metric for fan efficiency and is determined by dividing the total electrical power of the fan in an AHU by the highest airflow in either supply or exhaust. A lower SFP indicates greater system efficiency which implies reduced energy use for fans. Achieving this involves selecting an efficient fan that minimizes pressure drop and optimizing duct and AHU design. Calculating SFP alongside the knowledge of electricity prices informs us about ventilation costs. What's worth noting is that a system's SFP is not always constant but fluctuates based on factors like filter condition and RPM, (Swegon, 2021). To compare SFP across different products fairly, standardizing conditions is essential and therefore, there are three definitions for SFP, $SFP_{v,}$ and SFP_e. Both are used when calculating the fan power for individual units or fans where SFP_v calculates clean filters and dry heat exchanger and SFP_e calculates half dirty filters, intern leakage, condensation, and dry heat exchanger. (Svensk ventilation, 2021)

Older heat recovery systems have an SFP of around 3 kW/(m^3/s) and newer systems usually have around 1.5 kW/(m^3/s) with the potential to decrease even more and the SFP varies depending on the airflow in a DCV system (Svensk ventilation, 2021). This shows a significant reduction in energy demand in more recent models. According to Boverket, SFP_v should not exceed 1.5 kW/(m^3/s) for a system with heat recovery. However, if the airflow can vary with a flow rate lower than 0.2 m^3/s or operational hours are less than 800 per year, a higher SFP_v is deemed acceptable, (Boverket, 2020). The formula for calculating the SFP can be seen in Equation 1. (Warfvinge & Dahlblom, 2010)

$$SFP = \frac{P_{sf}+P_{ef}}{q_{max}} \qquad (1)$$

P_{sf} = Total fan power of the supply air fans in kW
P_{ef} = Total fan power of the exhaust air fans in kW
q_{max} = Highest airflow in either supply or exhaust in m^3/s

2.3.4 Heat Recovery

In the pursuit of greater energy efficiency, the incorporation of heat recovery systems stands as a significant strategy. It is integrated with mechanical fans to ensure controlled air circulation and ventilation rates. The investment cost can be high and more frequent maintenance is required compared to other systems e.g. filters need to be checked, cleaned, and changed at least one time a year and there is a risk of noise generation if not installed properly. Heat recovery ventilation is composed of four duct systems, supply air, extract air, air intake, and exhaust air, see Figure 4. (Warfvinge & Dahlblom, 2010)

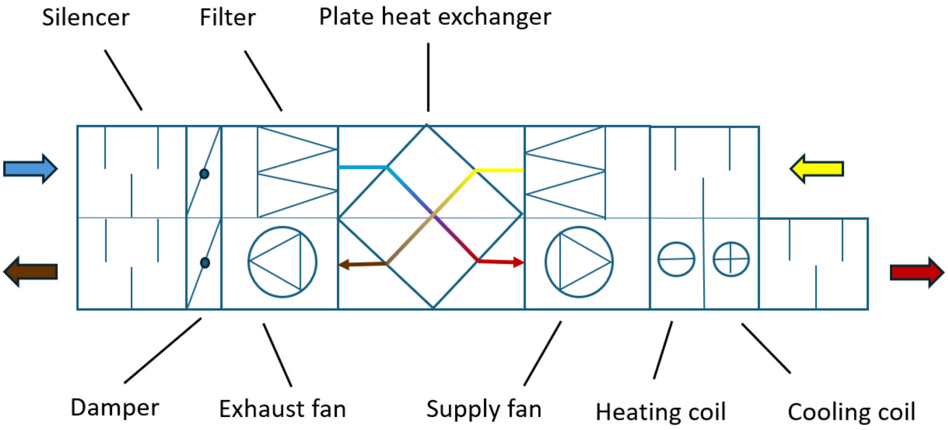


Figure 4. Air handling unit and its components (Inspired by Swegon).

The heated exhaust air, once extracted passes through various components of the air handling unit including the sound damper, filter and heat exchanger where it reclaims the heat before being discharged through exhaust ducts. Simultaneously, fresh cold supply air is drawn into the air intake ducts where it passes through the silencer, damper, and filter, and is heated by the recovered energy from the heat exchanger. The amount of energy recovered varies based on the type of heat exchanger where the potential of reclaiming energy can vary between 50%-80%. Supply ducts are usually placed under exhaust ducts to prevent the mixing of air and to utilize natural convection where warm air tends to rise and cold air to fall. The main types of heat exchangers are plate, rotary, and run-around coil heat exchangers and these can have different flow arrangements being parallel, counter, and crossflow, (Warfvinge & Dahlblom, 2010).

A plate heat exchanger falls under the broader category of recuperative heat exchangers, see Figure 5, (Eurovent, 2018). It is widely used in various industries for its compact design and can have different flow arrangements which impacts the efficiency of the system. The different flow configurations are parallel, counter, and crossflow with cross and counterflow being the most common ones used. In the process, supply, and exhaust air pass each other separately where the hot exhaust air heats the metal sheets while the cold supply air absorbs the heat. (Rec indovent, 2019) The heat exchange occurs without direct fluid contact which minimizes contaminations. Parallel flow is least effective with an efficiency of around 50% as hot and cold mediums flow in the same direction allowing air to mix at the exchanger entrance. Crossflow has an efficiency of 60-75% where the hot medium flows perpendicular to the cold and it offers a compact design. Counterflow is the most optimal arrangement with an efficiency of around 90% where the hot medium flows in the opposite direction and prolongs the interaction between air streams due to larger cross-sections. (Svensk ventilation, u.d.)

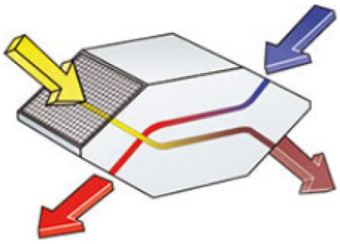


Figure 5. Plate Heat Exchanger (Taken from Svenskventilation).

A rotary heat exchanger falls under the category of regenerative heat exchangers, see Figure 6, (Eurovent, 2018). In this mechanism, the wheel is heated by the hot exhaust air which then warms the cold supply air as the wheel is continuously rotating between the supply and exhaust air ducts. While achieving an efficiency of around 80%, a drawback lies in the potential risk of odour and contamination leakage from exhaust to supply air which makes it less preferable compared to plate heat exchangers, particularly in environments with elevated pollutants like restaurants. A Rotary heat exchanger is recognized for their low-pressure drops, resulting in minimal fan energy demand. (Svensk ventilation, u.d.) During summer when temperatures rise, the heat recovery system continues to capture unwanted heat. To prevent this, the heat exchanger should be equipped with speed control regulations to reduce the speed of the wheel from around 20 RPM to 0.5 RPM, thereby decreasing the efficiency of heat recovery. Rotary also pose a risk of condensation during colder months where warm exhaust air can condensate in the exchanger and freeze to ice, however, this can be avoided by lowering the RPM, (Warfvinge & Dahlblom, 2010).

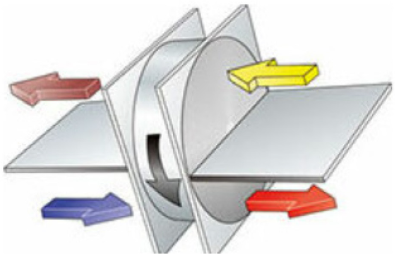


Figure 6. Rotary Heat Exchanger (Taken from Svenskventilation).

Run-around coils are indirect recuperative heat exchangers where heat is transferred indirectly between two coils, one supply air stream and one exhaust air stream see Figure 7, (Eurovent, 2018). These coils are connected by a closed loop containing a heat-transfer fluid which is typically an antifreeze solution and acts as an indirect medium between the two air streams. The heat from the exhaust air is first absorbed by the liquid in one coil and then transferred to the supply air in another coil. This type of system provides great flexibility as the coils can be placed independently and achieve an efficiency of approximately 70%. Run-around coils are used in premises with high contamination risks, such as hospitals and laboratories, ensuring that supply and exhaust air remain separate, (Svensk ventilation, u.d.).

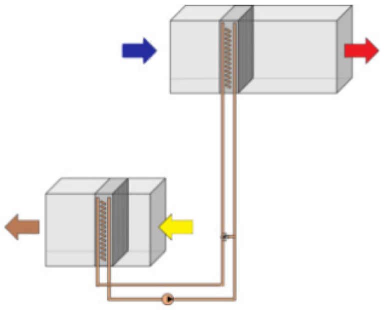


Figure 7. Run-around Coil (Taken from Svenskventilation).

The efficiency of the heat exchanger is defined by the heat exchanger efficiency for both the supply and exhaust air, see Equations 2 and 3. However, the report does not calculate these values since its already given by FläktGroup, (Warfvinge & Dahlblom, 2010).

$$\eta_s = \frac{T_h+T_{out}}{T_r+T_{out}} \cdot \frac{q_s}{q_e} \tag{2}$$

$$\eta_e = \frac{T_r+T_e}{T_r+T_{out}} \cdot \frac{q_s}{q_e} \tag{3}$$

T_h= Temperature after the heat exchanger in °C
T_{out} = Temperature outside in °C
T_r = Temperature of the extract air in °C
T_e = Temperature of the exhaust air in °C
q_s = Supply airflow in m^3/s
q_e = Exhaust airflow in m^3/s

The purpose of other components within the AHU such as a silencer plays a crucial role in minimizing noise generated by fans and the airflow within ducts. On the other hand, dampers serve a dual purpose as they regulate the volume of air and act as a protective measure against the potential spread of fire, (Warfvinge & Dahlblom, 2010). Smart dampers can also regulate the temperature in different parts of the school and adapt the ventilation rate according to the number of occupants by knowing the CO_2 level in the classroom or humidity levels in the showers. This will make it easier to maintain an even and good temperature and thus reduce energy use. Recognizing the external air's contamination with particles and gases, a filter is installed to ensure cleaner intake. Additionally, the heating and cooling coil comes into play which allows temperature regulation based on the user's need, (Sveriges Kommuner och Landsting, 2011).

2.4 Energy-efficient design strategies

It is important to aim for an energy-efficient design to reduce the energy use of the ventilation system during the operational period. This could be achieved by mainly reducing the pressure drop and having high efficiency in the ventilation system by optimizing the duct system design, fans, and component selection, and adjusting the system type by implementing techniques that allow controlled demand ventilation. (Warfvinge & Dahlblom, 2010)

2.4.1 Duct system design

Ventilation ducts are made of sheet metal usually referring to galvanized stainless steel or aluminium metal and come most typically in round or rectangular shapes. Circular ducts are made of screw-folded metal sheets and are preferred over rectangular ducts because they are more airtight with minimal leakage, offer a smooth airflow by efficiently utilizing the cross-sectional area, and are more aerodynamically efficient, reducing friction and pressure drop. Circular ducts also have a lower production and installation cost making it more preferable to rectangular ones. However, rectangular ducts are preferred in limited spaces such as false ceilings where high airflow is required. Duct dimensions and steel thicknesses are standardized to simplify installation but vary depending on airflow volume. (Spiral Manufacturing, 2021)

Energy-efficient design of the duct system aims to reduce the energy use and noise generation from the fan by reducing the air velocity and pressure loss in the ducts. This can be achieved by using a larger dimension for ducts. However, the disadvantage is a greater space requirement in addition to using more material and transport and therefore having a higher cost and perhaps a greater environmental impact in the construction phase. An additional advantage to reducing the operational energy with larger duct dimensions is having a more flexible ventilation system that can adapt to any changes in the function of the building upon renovation since it can tolerate greater amounts of airflow within the system. Alternatively, energy use for the ventilation system can be reduced with a reduced duct size only in the case where the designed airflow volume is decreased when having a VAV or DCV system that allows such a transition. Smaller duct dimensions require less space and will reduce the cost and installation time. However, the pressure drop and fan efficiency will be higher to compensate for the same amount of airflow. (Warfvinge & Dahlblom, 2010)

2.4.2 Type of mechanical ventilation system

Mechanical ventilation can lower the cost and environmental impact during the usage phase and mitigate the concentration of carbon dioxide, heat, and humidity released by students in a classroom, thus improving the indoor climate (Svensk ventilation, u.d.). The most straightforward traditional approach to ventilate a building using mechanical ventilation is through constant air volume (CAV), where the building ventilates continuously throughout the day even when there is no demand. The installation cost is low and suitable for rooms with a consistent need for ventilation and low fluctuations in both occupancy and heat load during operational hours. However, premises are often used to varying degrees throughout the day, for example, classrooms will not be utilized 100%, which is why using a demand control system will save energy. (Exhausto, u.d.) Hence, the concept of controlled ventilation is introduced to address these challenges as it can potentially reduce the need for cooling, heating, and ventilation by 10-30% (Svensk ventilation, n.d.).

Mechanical ventilation can be variable air volume (VAV) or demand control air volume (DCV) and the purpose of both is the same, to adjust the ventilation according to the level of activity in the room. However, there are some differences between these two, VAV is more a simple system where the air volume varies according to a schedule adapted to temperature or air quality. Smaller and lighter projects, such as preschools, often meet the requirements and needs and provide better energy savings compared to a CAV system, while the investment costs are lower compared to a DCV system. (Swegon, n.d.) A DCV system is a more advanced system that comes with a higher investment cost where the airflow can be regulated by monitoring temperatures, CO_2 levels, occupancy, or humidity (Exhausto, u.d.). It has the potential to combine air and waterborne products to provide a more comfort level and the flow regulation can be achieved using either motorized active flow dampers or active diffusers. To prevent disruption to air supply in other rooms, it's essential to incorporate pressure sensors and retainers in the duct system. Additionally, to maintain pressure balance within the room, exhaust diffusers should also be flow-regulated following the same principles as supply diffusers. (Warfvinge & Dahlblom, 2010) A distinction between VAV and DCV is that VAV can reduce airflow by 72%, while DCV achieves a more significant reduction equal to 84%, compared to a CAV-system (Swegon, 2018)

2.5 Life cycle assessment - LCA

LCA stands for Life Cycle Assessment and is defined by the ISO 14040 standard as a method to assess potential environmental impact to achieve environmental goals. LCA is the best current framework according to the European Commission, to evaluate the environmental impacts throughout a product´s life cycle from raw material to disposal. LCA applies to building certifications such as BREEAM and can be performed using environmental labels such as Environmental Product Declarations (EPD). It can be applied to the whole building or even different building components and elements to quantify their environmental impact. (Schlanbuscha, o.a., 2016) LCA is based on four main phases according to the ISO 14040 standard and the four phases included are goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and interpretation (Finnveden & Potting, 2014).

The assessment of LCA can be approached in two ways, conventional LCA and dynamic LCA. Conventional LCA is the most frequently accounted for and aggregates all the emissions occurring at a specific point of time, thus not accounting for the time at which the emission will occur. This will lead to inconsistency between the time horizon chosen for the analysis in each LCA study and the period covered by the results. Conventional LCA calculates an instantaneous emission of all environmental impacts, thus it will not reflect the reality that the emissions will be released at a small rate over several years. Conventional LCA will therefore decrease the accuracy when analysing a system over longer periods, however, dynamic LCA will consider changes over time. (Borg, 2016)

2.5.1 Goal and scope definition

The goal and scope definition includes specifying the reason for the study, and the method in which the LCA is performed by defining the system boundaries and functional unit. The functional unit is both quantitative, describing the amount and qualitative describing the properties which allows comparison between systems. Part of the system boundary that needs to be specified is the life stages included in the study. The building life cycle stages are A1-A3 (Production), A4-A5 (Construction), B1-B7 (Use), C1-C4 (End of life) and D (Reuse). Figure 8 illustrates what these stages include. (Hassan, 2019)

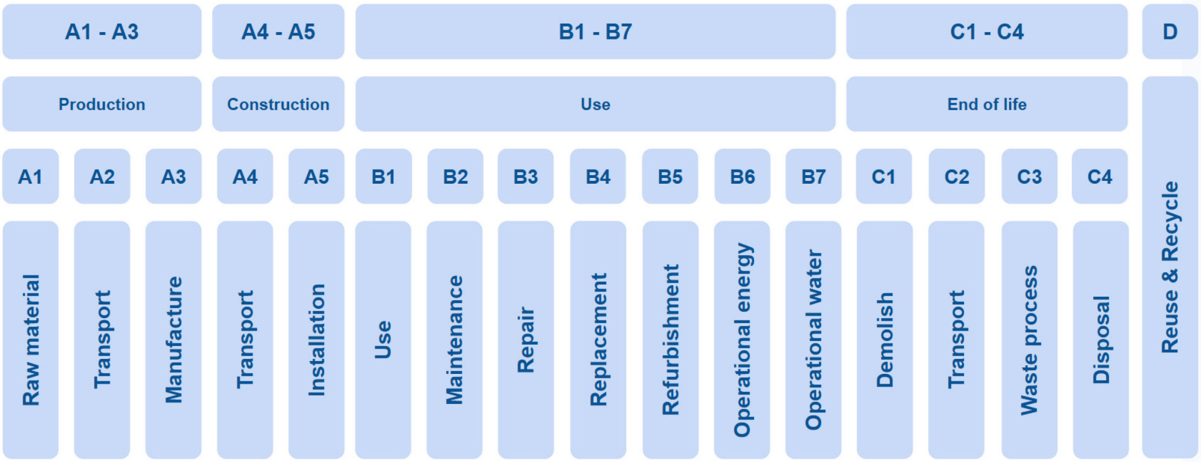


Figure 8. Different stages of a life cycle analysis (inspired by Skanska).

The system boundary of an LCA study can be cradle to gate, cradle to grave, gate to grave, or cradle to cradle. Where cradle to gate mainly includes the production stage and the cradle to grave includes the manufacturing, use, and end-of-life stages. Gate to grave includes the use and end-of-life stages while cradle to cradle includes all stages from manufacturing to reuse and recycling. To calculate the environmental impact the calculation period for the item needs to be defined along with its lifespan and life cycle stages. (Hassan, 2019)

2.5.2 Life cycle inventory analysis (LCI)

In the life cycle inventory analysis (LCI), the use of energy, natural resources, and material requirements in addition to environmental emissions within the system boundary defined are quantified. Performing an LCI incorporates the development of a flow diagram and data collection. The flow diagram includes all processes (e.g. transports and energy supply) that create the product system and the different inputs and outputs of these processes. In addition, elementary flows are included which consist of material or energy flows to and from the system, drawn from the environment (e.g. land use, energy, and material resources) or disregarded to the environment (e.g. emissions). (Schlanbuscha, o.a., 2016) Datasets related to material consumption, wastes, and emissions can be collected from primary databases where measurements, models, and detailed information are provided by manufacturers and product reports, (Farjana, Mahmud, & Huda, 2021).

2.5.3 Interpretation of result

The final phase of LCA involves interpreting the results, which should align with the study's goals and scope. It's a systematic approach to identifying, evaluating, and summarizing information derived from the results of LCA. The outcome of this interpretation phase is the study's conclusion and recommendations, which should include the following: (Nieuwlaar, 2013)

- Identification: Establishing the structure of the results to determine significant issues.
- Evaluation: Enhancing the sensitivity and reliability of the results, making them understandable to other parties.
- Conclusion: Drawing conclusions and outlining limitations, to provide future recommendations for the intended audience

2.5.4 Environmental impact categories

Environmental impacts are the consequence of elementary flows on ecological health and resource depletion (Nieuwlaar, 2013). There are many environmental impact categories such as global warming potential, abiotic depletion potential, acidification potential, Eutrophication potential, and Ozone depletion potential. However, in line with most certifications, methods, and guidelines, Global Warming Potential (GWP) is the category frequently chosen and required in a climate declaration in the building sector. (Boverket, 2019)

There are four definitions of GWP, GWP-fossil, GWP-biogenic, GWP-land use and land use change (luluc), and GWP-total (the sum of the other three GWP indicators) (The international EPD system, 2022). Some methods and guidelines prefer the use of Global Warming Potential-Greenhouse gas (GWP-GHG) which excludes the uptake and release of biogenic carbon dioxide to enable a direct comparison of the impact between two products and their production. (Boverket, 2023) Generally, GWP contributes to warming the earth by its ability to absorb energy and delay it from exiting the atmosphere. GWP is a measure of the energy amount absorbed by the emissions of 1 ton of gas relative to the emissions of 1 ton of carbon dioxide (CO_2) over the same period of time. The unit is therefore in kg CO_2-equivalent. (Environmental Protection Agency, 2024)

2.6 LCA methods & guidelines

The Swedish government has introduced new regulations constituting that all newly constructed buildings from the beginning of 2022 must undergo climate declaration and report their climate impact. Various methods and guidelines are available for conducting climate calculation and declaration, and the results may vary depending on the method chosen. (Boverket, 2023)

2.6.1 The international EPD system

The international EPD system was initially founded as the Swedish EPD system by the Swedish Environmental Protection Agency (SEPA) and industry and is the world's first and most extended operational EPD program (The International EPD System, u.d.). It describes the environmental impact of products and services from a life cycle perspective with system boundaries cradle-to-grave (A-C). EPD is third-party verified based on ISO 14025 and EN 15804 and can be applied for all types of products such as material, transport, and energy sources. The international EPD system has climate data for district heating for different locations in accordance with ISO 14025. The available EPDs for Swedish electricity come from a cogeneration or average value of 13.8 g CO_2e /kWh. (Hinsegård & Vitanc, 2023)

2.6.2 Boverket

Boverket, the Swedish National Board of Housing, Building, and Planning, is a governmental organization responsible for developing regulations and providing general guidance for construction projects. New buildings must meet the requirements for a climate declaration aligned with Boverkets regulations. (Sweden Green Building Council, u.d.) Boverket LCA standard consists of two standards that are being used within the building industry, SS-EN-15978:2011 comprises the whole building and SS-EN 15804:2012 + A1:2013 comprises a building product. According to Boverket, the system boundary for the climate declaration for buildings should include life cycle stages A1-A5, covering activities from raw material extraction to installation. This process should adhere to the European standard EN 15978. (Boverket, 2019) The general requirements are mainly more specific for the building envelope. The functional unit in which the environmental impact must be reported is kg CO_2e/m^2(GFA). Calculation tools used should be adapted to Boverket's climate database. (Sweden Green Building Council, u.d.).

Boverket presents both specific and generic emission factor values. Specific climate data is based on existing EPDs reflecting more of the actual impact of a product, so the calculated impact is generally lower if specific climate data is used. Generic climate data from the climate database of Boverket are derived from data provided by the Swedish Environmental Research Institute (IVL) which is based on a calculated average from existing Environmental Product Declarations (EPDs) for construction products used in the Swedish market. However, these values are set 25% higher than the average. Regarding climate data for energy and fuel, emission factor value for district heating is sourced from the Swedish Environmental Protection Agency, and electricity from IVL, see, Table 2. (Boverket, 2023).

Table 2. GWP emission factor derived from Boverket Climate Database.

Energy source	**GWP: B6 /(g CO_2e /kWh)**
District heating	56
Swedish electricity mix	37

2.6.3 NollCO2

NollCO2 was founded by the Swedish Green Building Council (SGBC) and serves as an extension to their certification systems such as Miljöbyggnad, BREEAM-SE, LEED, and Svanen. It operates with three standards: SS-EN 15804:2012 + A2:2019, SS-EN 15978:2011, and SS-EN ISO 14021:2017 2017. NollCO2 aims to achieve net-zero emissions, thus it includes the entire lifecycle of buildings (A-C) over the period of 50 years. Specifically, carbon limits have been established for A1-A3 to contain climate impact within the modules, while A4-A5 are subject to a static energy carbon limit and an energy performance limit for module B6. (Sweden Green Building Council, u.d.)

NollCO2 lacks a comprehensive set of generic climate data and relies therefore on various databases in a specific order of priority for calculating stages A1-A3. Firstly, it references EPDs and if EPDs are unavailable, generic values from Boverket's National database are referred to and if Boverket's database is unavailable, the German database Ökobaudat is consulted as a third option. For B6 climate data concerning district heating and electricity, EPDs are prioritized. In the absence of EPDs, NollCO2 uses its average generic value for district heating derived from the Swedish Environmental Protection Agency, and similarly, climate data for the Swedish electricity mix relies on NollCO2's generic value calculated using a geographically based approach, EU JRC's model, see Table 3. (Sweden Green Building Council, n.d.)

Table 3. GWP emission factors derived from NOLLCO2.

Energy source	**GWP: B6 /(g CO_2e/kWh)**
District heating	60
Swedish electricity mix	22

2.6.4 Energiföretagen Sverige - Swedenergy

Swedenergy is an organization that consists of different energy companies that produce, distribute, sell, and store energy (Energiföretagen, u.d.). The dominant company within Swedenergy is the Swedish government that owns Vattenfall, second place is the German state, Uniper followed by the Finish state, Fortum. Swedenergy is a member of the Heating Market Committee (VMK) and provides average carbon dioxide emission factors to district heating companies from VMK. Energiföretagen has climate data for district heating for different locations. The electricity is based on the Nordic residual mix from The Swedish Energy Markets Inspectorate which has a higher emission factor compared to the Nordic and Swedish electricity average. This is because it excludes renewable energy sources and mainly includes non-renewable sources such as fossil fuels. The emission factor for GWP for the Nordic residual electricity mix is 372 g CO_2e/kW. (Hinsegård & Vitanc, 2023)

2.6.5 BREEAM

To receive 2 points in BREEAM, LCA must be carried out for indicator GWP (Global Warming Potential)-GHG (Greenhouse gas) for all life cycle stages including production; module A1–A3, construction; module A4–A5, usage; module B1-B7; final stage, module C1–C4 and D, Impact beyond the system boundary. The life service of building elements included in the calculation should be defined unless further information is provided in the chosen calculation method or software. In regards to installations, the technical lifespan of an air handling unit as defined by EU levels is 20 years and for other parts of the air handling system, it is 30 years, which applies in case no further information is provided by the contractor or manufacturer of these components. The calculation period is an average of one year of the reference study period of 50 years. The functional unit in which the environmental impact must be reported is kg CO_2e /m^2 (BTA). (Sweden Green Building Council, u.d.)

To reach 3 points in BREEAM, the percentage improvement in comparison to the reference value for all stages of a life cycle assessment should follow the percentages provided by BREEAM. The reference value for the environmental impact of a preschool is 258 kg CO_2e/m^2(GFA). Since this study is limited to an LCA for only one building element, the ventilation system, the overall guidelines of the LCA will be followed but no point awarding system or reference values will be applied. (Sweden Green Building Council, u.d.)

2.7 Life cycle cost - LCC

Conducting an LCC helps meet economic objectives in sustainable development. Purchases of goods and services for long-term use are often seen as investments. Historically, the primary focus when making a purchase has been solely on economic evaluation, often referred to as conventional LCC. (Pre sustainability, 2022) This approach prioritizes obtaining the lowest price for the product or service in the belief that it represents the best investment. However, as industries are moving towards a higher degree of sustainability, there is a growing importance and popularity in evaluating a product's entire life cycle cost when making purchasing decisions. (Ivprodukt, u.d.)

Through LCC analysis, a holistic examination of total expenses over a product or service's lifetime is considered, from purchase to disposal or waste. This comprehensive assessment comprises three key parameters: investment, operational, and maintenance costs, and by thoroughly evaluating these aspects over time, LCC enables potential savings and comparisons between different options. It also ensures economic feasibility along with environmental sustainability. (Upphandlingsmyndigheten, u.d.) The principle for LCC can be described using the iceberg phenomenon. The top of the iceberg refers to the purchase or investment in a product and it represents as little as 10% of the total cost, while the remainder consists of operation, maintenance, and service costs accounting for up to 90%. (Ivprodukt, n.d.)

In addition to evaluating costs, an LCC analysis also determines the respective payback period and the duration at which each installation starts to generate energy cost savings. However, estimating energy and maintenance expenses can pose challenges due to fluctuating interest rates influenced by various economic factors such as inflation and countries economic status. It is therefore difficult to predict the economic feasibility and payback time because it is affected by these fluctuations. Interest rates may be categorized as nominal or real, with the nominal rate being the real interest rate along with inflation. (Ivprodukt, u.d.)

Another important factor is the consumer price index (CPI) which includes the effect of all prices including the household mortgage rates, thereby impacting the inflation rate. The Swedish Riksbank prefers the use of the Consumer Price Index with a Fixed Interest Rate (CPIF) to provide a more accurate picture of inflation, as CPIF excludes the effects of housing costs and the annual change in the CPIF should be around 2%, meaning the price level should increase by an average of 2% compared to the same period in the previous year. (Sveriges Riksbank, 2023)

2.8 Intergraded life cycle assessment (ILCA)

An Integrated Life Cycle Assessment (ILCA) offers a comprehensive evaluation of a product or process by combining aspects of both Life Cycle Assessment (LCA) and Life Cycle Costing (LCC). It converts environmental impact assessment into a single score, allowing decision-makers to assess the sustainability of various options by considering both environmental and economic factors at the same time. To achieve this, two important concepts need to be considered, normalization and weighting. (Meynertsa, Götzea, Clausb, Peçasc, & Ribeiroc, 2017)

Normalization is used to combine the different units of the environmental impacts into one unitless value to compare results and allow interpretation. This process can be calculated through internal or external normalization. By internal normalization, a maximum, summation, or baseline value is used as an internal reference point against which the characterized environmental impact can be divided, within each impact category. An external normalization uses global reference values that are independent of the LCA's object, such as a company or region. Instead, these values are based on production or consumption. (Deiso, 2022)

Weighting is the process of converting normalized environmental impacts into weighted environmental impacts through the application of weighting factors. It involves combining various normalized environmental impacts into a single index by assigning relative importance to each impact category. This allows for a more balanced assessment by considering which impacts are of greater concern. Subsequent to the normalization and weighting of LCA separately, an environmental and economic weighting factor is determined to calculate the overall performance of the investigated case upon combining LCC and LCA. (Deiso, 2022)

2.9 LFM30

LFM30 is an organization established to expedite the construction sector's transition to climate sustainability and the implementation of Agenda 2030. LFM30 aims to reduce the climate impact to half by 2025 and have Malmö become a climate-neutral city by 2030. Post 2030, the objective is to contribute to a climate-positive construction and infrastructure sector by 2035. To attain these goals, LFM30 has devised commitments divided across six strategic focus areas, AG1-AG6, where AG3 and AG5 focus on the design, process, and climate calculation respective climate-neutral management, operation, and maintenance. (LFM30, u.d.)

2.9.1 Climate Staircase

LFM30's way to achieve the goals set can be described in a climate staircase divided into four steps, illustrated in Figure 9, below, (LFM30, 2022).

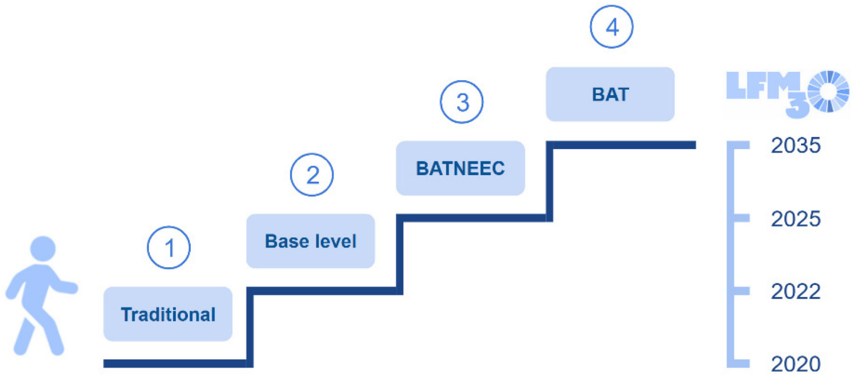


Figure 9. LFM30:s climate staircase (inspired by LFM30)

These climate steps were described as follows: (LFM30, 2022)

- Step 1 (Traditional level) consists of legal requirements to calculate the environmental impacts for stages A and B.
- Step 2 (Base level) includes Investigating different energy- and environmental-efficient measures without additional costs.
- Step 3 (BATNEEC) includes following the best available energy- and environmental-efficient techniques not entailing excessive costs.
- Step 4 (BAT) has a more flexible approach to cost but should still be within realistic margins. Allows a flexible implementation of energy- efficient and environmental design strategies.

2.9.2 Climate budget – LCA

A climate calculation, LCA can be conducted according to the LFM30:s climate budget document. The workflow is divided into five stages; Calculate, Improve, Target limit value, Negative emissions, and Continuous monitoring. These stages described in a simple way what is included by the following: (LFM30, 2022)

1. Calculation: Climate calculations are conducted according to standard EN15978 and EN 15804 with system boundaries A1-A5, and operational stage B6, analyzed over 50 years.
2. Improvements: Various climate improvement measures are tested to ensure compliance with LFM30:s target limit value. This step can be performed after completing the initial climate calculations. The climate staircase by LFM30 can be utilized in this step.
3. Target limit value: Different target limit values are set for buildings and facilities, measured in CO_2e/ light BTA m^2. New constructions have target limit values for A1-A5 and B6.
4. Negative emissions: A repayment plan is formulated to address the climate impact caused by buildings in terms of greenhouse gas emissions. Repayment can occur through negative emissions ($-CO_2e$) or emission prevention.
5. Continuous monitoring: Continuous follow-up of previous stages is conducted to balance and account for changes in CO_2e emissions during use.

Climate data is calculated following standard EN 15804, using the GWP-GHG unit of kg CO_2e. In cases where information about a product is missing, compensation is necessary to ensure a high level of climate data coverage. Within LFM30, EPDs are given priority for use, and if EPDs are unavailable, generic data is utilized. The generic data have various sources, prioritized according to a list with Boverket's database at the top. (Samuelsson & Wiik, 2022)

3 Literature Review

3.1 Mechanical ventilation systems

A previous study provided several alternatives for an HVAC system for a modern Swedish office building including a CAV and VAV system. The CAV system had the highest energy use in comparison to the other systems, where almost 20% was for fan energy. The reduction in the total energy use for the VAV system relative to the CAV system was 50%. (Hassan, 2019) Another study investigated implementing VAV ventilation instead of CAV ventilation in new and retrofitted buildings. Reducing the airflow rate from 0.35 to 0.1 l/(s, m^2) during unoccupied hours can result in a saving equal to 30% for the fan energy and 20% of the energy used for preheating supplied air. This is while having the air flow rate at the normal level, two hours before the occupants are in the building to ensure acceptable indoor air quality. (Hesaraki, Ploskic, & Holmberg, 2015) The potential application of demand control ventilation in schools was investigated in a study conducted in Norway. The aim was to reduce the designed airflow and energy demand by combining demand control ventilation with displacement ventilation (DCDV) equipped with CO_2 sensors. Comparative analysis with traditional constant air volume (CAV) systems revealed a substantial reduction in air volume equal to 50%. Additionally, the study showed a significant decrease of 21% in the total heating demand, with 54% attributed to heat recovery in the ventilation system. Assuming constant fan efficiency, the energy use of the ventilation fan could be cut by 87% over the one-week analysis period with a DCDV system. (Wachenfeldt, Mysen, Schild, & Schild, 2007) In newly constructed preschools the predominant ventilation system used is Exhaust and supply air ventilation with heat recovery and the preferable flow system are demand control system with variable air volume. Extensive research on displacement and mixing ventilation indicated that displacement flow improves air quality and reduces health issues among children considering that examining pollutant levels at different heights revealed lower levels near the floor with displacement flow. Additionally given the tendency of children to play on the floor, displacement flow may be preferred. However, the study concluded that the choice of ventilation principle is inconsequential as long as the airflow supply is adequate. (Sveriges Kommuner och Landsting, 2012)

3.2 Occupancy level

Occupancy level and behavior are some of the main aspects that can affect the amount of energy that can be saved in a demand control ventilation system. A previous study investigated occupancy behavior and level of students in several schools in Norway and its impact on the energy efficiency in ventilation systems. Three ventilation strategies were analyzed: Constant air volume (CAV), CO_2 sensor-based demand-controlled ventilation (DCV-CO_2), and infrared occupancy sensor-based demand-controlled ventilation (DCV-IR). Systems CAV and DCV-IR were designed for the maximum number of students with an airflow of 7 l/s per person and 1 l/s per m^2. System DCV-CO_2, on the other hand, was designed for the actual number of students, maintaining a minimum of 1 l/s m^2 when CO_2 levels were below 700 ppm. The results showed an average occupancy level equal to 74% of the maximum designed number of occupants when in use. Systems DCV-CO_2 and DCV-IR demonstrated energy savings of 30% and 51% respectively, compared to the CAV system. (Mysen, Berntsen, Nafstad, & Schild, 2005) Another study was conducted to investigate the occupancy levels in several classrooms in Sweden. The investigation involved measuring airflow rates in rooms equipped with Variable Air Volume (VAV) systems, as well as monitoring carbon dioxide concentrations. These classrooms were designed to accommodate approximately 24-30 individuals, yet the findings revealed an occupancy level of nearly 20% over the working period. Uncertainties encountered during measurements included the determination of the actual airflow rate change due to factors such as leakage and buoyancy affecting the air within the classroom, as well as instances of window airing. Additionally, carbon dioxide levels were influenced by factors such as burning candles and the presence of plants, while human activity and body mass variations also contributed to fluctuations in carbon dioxide production. (Johansson & Bagge, 2012)

3.3 Carbon Dioxide generation rate

A study on Carbon dioxide generation rates for children and adolescents complements a lack in previous studies since there are limited studies on CO_2 generation rates of children however numerous on CO_2 generation rates of adults. The study synthesizes data for CO_2 generation rates for children and adolescents aged 5–18 years for various activity levels summarized in a table for further research use. The results indicate that the carbon dioxide generation rate varies depending on clothing, activity level, and age. It has been indicated that gender differences do not have effects on the CO_2 generation rate before the age of 15 years. Children between the ages of 5 to 12 years have significantly lower CO_2 generation rates in comparison to adults. Table 4, shows the values for CO_2 generation rates in l/s for different activities. (Wu, o.a., 2023)

Table 4. Carbon dioxide generation for adults.

Level		**Sedentary**		**Low intensity**		
Activity		Games	Television	Sweeping	Playing	Dance
CO_2 Generation rate /(l/s)	Boys	0.0029	0.0017	0.0073	0.0041	0.0049
	Girls	0.0026	0.0019	0.0069	0.0044	0.0054

Carbon dioxide generation rates for adults are also dependent on gender, age, and activity level. The CO_2 generation rate is significantly higher for adults in comparison to children and specifically for males. Different activities result in different metabolic rates characterizing human energy consumption and resulting levels of CO_2 production. Activities that demand a higher metabolic rate result in a higher CO_2 generation rate. Activities and the corresponding CO_2 production for both males and females between the ages of 30 and 50 are presented in Table 5, below. (Persily & Jonge2, 2017)

Table 5. Carbon dioxide generation for children.

Activity		**Childcare**	**Light calisthenics**	**Cleaning**	**Kitchen**	**Walking**
CO_2 Generation rate /(l/s)	Male	0.0134	0.0115	0.0154	0.0116	0.0134
	Female	0.0104	0.0089	0.0119	0.0091	0.0104

3.4 LCA

Old LCA studies have shown a tendency to place a greater weight on an individual stages of the life cycle assessment of a building being either the construction or operational stage. For a ventilation system, the operational stage is considered to be the one with the significant environmental impact in comparison to the construction stage. However, it is worth considering that this larger environmental impact in the operational phase stems from the use of primary sources of energy. (Borg, 2016) Therefore, having renewable energy sources can reduce the negative contribution the operational phase has. (Jerléus, 2020) Based on the results of a previous study conducted on the life cycle assessment of buildings in various countries, embodied energy from the construction and demolition phase only represents 10%-20% of the building's total environmental impact while 80%-90% stems from the operational phase, mainly due to equipment, lighting, heating, cooling and HVAC systems. (Nilsson Willkomm, 2020) Another study based on an office in Norway concluded that the impact from the operational stage has a larger environmental impact over the system's lifespan. The ventilation system accounts for almost 22-33% of the total energy use of the building and thus the environmental impact during the operational period, mainly due to the electrical need for fans. (Borg, 2016) Based on a previous study regarding experiences with LCA in the Nordic Building Industry the challenges, needs, and solutions encountered were identified. The results show a lack of knowledge on which strategies have the biggest impact on the LCA of a building. There is also missing data and guidelines for assessments for the usage stage of the building life cycle. A better understanding of the significance of the type of heating and the effect of local/on-site energy production is needed in the operational stage. The participants also emphasized the importance of considering impact categories other than global warming potential. There is a need for a better understanding of how LCA could be used for renovation projects. (Schlanbuscha, o.a., 2016)

4 Method

4.1 Case study

Based on an investigation conducted by SKR (Swedish municipalities and regions), a plan to build thousands of preschools was established. Several companies participated as contractors and four types of preschools differing in size were suggested, referred to as A, B, C, and D. The preschools have a standardized and identical design including the construction and installation based on type. Assemblin was enlisted for the design and construction of the four types of ventilation systems. (Assemblin, 2020) Two preschools, a two-story building with design concept D, Preschool A in Eslöv and Preschool B in Arlöv, were used as the case study to establish an understanding of the current design and create a base case. Preschool A is not yet in service but was used to model the ventilation system while Preschool B, was used for data collection for further analysis.

General information regarding the HVAC system of the preschools was retrieved from the technical description provided by the contractor and site visits. Operation hours for the ventilation system are according to the recommendations from BEN 2 being around 10 hours a day, five days a week, and 47 weeks a year, and the indoor temperature is set to a minimum of 22°C (Boverket, 2017). The heating system consists of floor heating with the demand being supplied through district heating. There are presence sensors in the hallways and most rooms, connected to the lighting system for the purpose of operating based on occupancy. Several rooms are also equipped with temperature, humidity, and carbon dioxide level monitors to track the level of thermal comfort. Located in the equipment room are panels that allow for remote control of the power, heating, and ventilation system.

4.1.1 Plan layout

Considering that Preschools A and B are based on a standard design, they both have the same plan layout presented in Figure 10. For simplicity, rooms with similar attributes were marked in the same color.

Figure 10. Plan layout for Preschools divided by space type.

The two floors have a similar layout and design and have a total heated floor area equal to 1850 m^2. The mutual area describes the places that cater to the needs of children by providing spaces for playing, resting, and eating. The larger storage area on the first floor is used as a cloakroom for the children while on the second floor, it is allocated for the use of the staff. The smaller storage spaces function solely as a storage room. The ventilation room on the second floor serves as a shaft for the ventilation ducts, connecting the second floor to the first floor.

4.1.2 Air handling unit

The preschool has a mechanical ventilation system and is equipped with two Air Handling Units (AHUs), LA01 and LA02, both situated in the ventilation room on the second floor. LA01 has a rotary heat exchanger and operates as a CAV system and supplies air to all rooms on both floors, except for the kitchen area while LA02 has a counterflow plate heat exchanger and operates as a VAV system supplying exclusively the kitchen area on the first floor. Having separate systems connected to two different air handling units prevents air from mixing. The model and size of AHU LA01 and LA02 are eQ Prime Side – 050 and eQ Prime Side – 008 respectively, see Figure 11. The gross floor area (GFA) designated for the ventilation system connected to LA01 and LA02 separately, is 1770 m^2 and 80 m^2 respectively. Both air handling units were designed by FläktGroup and the dry heat exchanger efficiency was determined according to SS-EN 308:1997, stating that the exhaust air should be equal to 25°C with a relative humidity of 27% and dew-point 5°C and the outdoor air temperature equal to 5°C, (Ventilation, 2012).

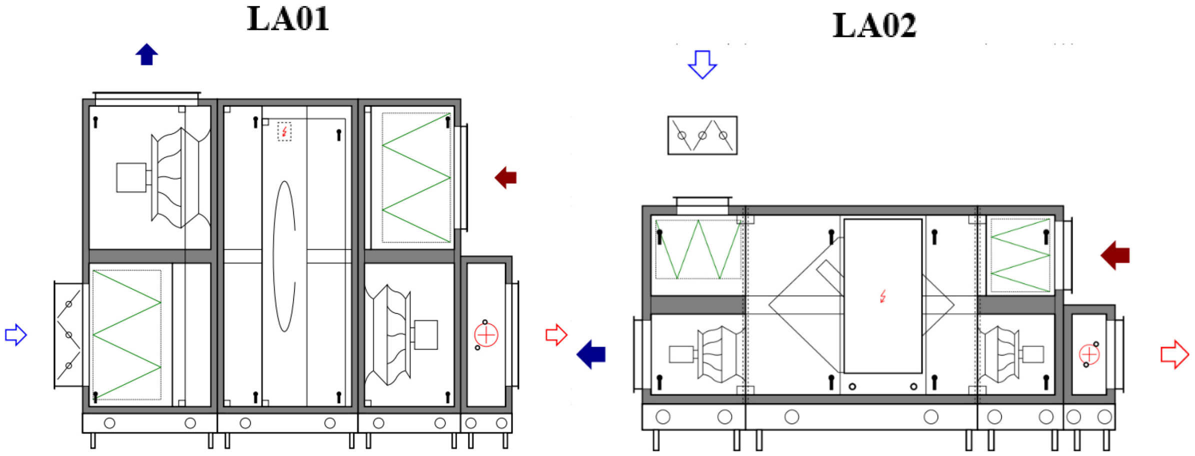


Figure 11. AHU with plate heat exchanger to the left is for LA01 and rotary heat exchanger to the right is for LA02.

Both air handling units consist of a radial fan with backward vanes and have a heating coil to heat the air to a comfortable temperature during the winter months. Both AHUs are not equipped with a cooling coil but during warm summer days the rotary heat exchanger for LA01 has a lower efficiency due to less RPM controlled by temperature sensors and the plate heat exchanger for LA02 has a bypass allowing the air to pass by, preventing unnecessary heating. There is potential for free cooling during summer nights when the indoor air has a higher temperature than outdoor air.

The functionality of the heat exchanger was limited to the winter months and therefore the efficiency of the dry heat exchanger was used in further calculations. Table 6, contains descriptions and features of both air handling units and the SFP$_v$ value was used to compare the two air handling units. It is worth mentioning that in situations where filters are dirty and other components such as the heat exchanger and coil are wet, the supply and exhaust pressure drop will increase by 50 and 60 Pa for LA01 and LA02 respectively for both supply and exhaust air.

Table 6. Input data for LA01 and LA02.

Description	LA01	LA02
Efficiency of dry heat exchanger /%	81.6	84.1
Max airflow – supply ; exhaust /(l/s)	4605 ; 4605	670 ; 685
Min airflow – supply ; exhaust /(l/s)	-	200 ; 205
Max pressure drop – supply ; exhaust /Pa	472 ; 478	409 ; 386
Min pressure drop – supply ; exhaust /Pa	-	340 ; 304
Fan efficiency – supply ; exhaust /%	70 ; 70	64 ; 64
SFP$_v$ /(kW/(m^3/s))	1.44	1.26

4.1.3 Ventilation system

The arrangement of the duct system is illustrated in Figure 12, and following the concept of mixing ventilation, the supply and exhaust air diffusers are three-way dispensed and are positioned to ensure that frequently used rooms have a sufficient air change rate. Subsequently, there are overhead air devices between some types of rooms for air transfer. The technique room is the only room that is not connected to the AHU, thus air is extracted and supplied through air grilles in the wall. Exhaust air diffusers are placed in areas prone to odors and pollutants such as kitchens, bathrooms, and hallways, effectively ventilating and extracting contaminated air. Supply and exhaust air terminals are by FläktGroup and mainly of the type RHKB for supply, and HPKH and GPDF for exhaust.

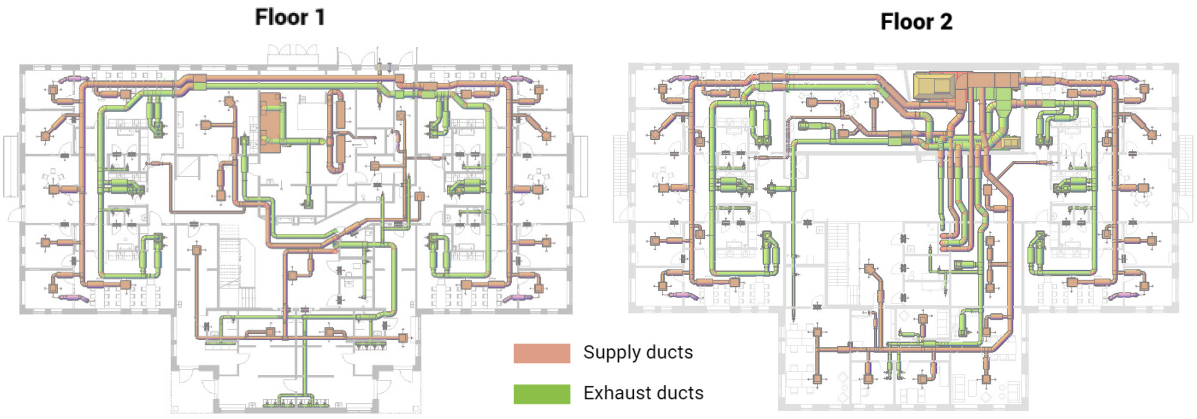


Figure 12. Duct system layout for the first and second floors.

The airflow in areas frequently visited by children was designed according to 0.5 l/s per m^2 and 7 l/s per person. However, for the staff department, the airflow was designed according to 0.35 l/s per m^2 and 7 l/s per person. The type of ducts used are mainly Lindab safe locked circular ducts of type SRL and rectangular ducts also by Lindab which were mainly used around the connection to the AHU. Silencers are of the type SLCU also provided by Lindab in different lengths and sizes.

4.2 LFM30

Designed energy-efficient measures will be placed under the relevant step according to the LFM30 staircase. Related to the optimization of the environmental impact of installations, more specifically the ventilation system, these steps include the improvement measures taken: (LFM30, 2022)

- Step 1 (Traditional level): This step does not include additional improvements or measures, it is mainly to report the current state of the environmental calculation of the project following a traditional approach.
- Step 2 (Base level): Related to this step is having alternative components that have the same initial cost but a lower environmental impact. Alternatively having an improved layout and design of the system would result in a lower amount of components. It is worth mentioning that this level was not investigated in this study and was considered a limitation.
- Step 3 (BATNEEC): This step includes implementing DCV strategies aiming to improve the environmental impact due to the operational stage.
- Step 4 (BAT): Related to this step is using recycled steel for the duct system including circular and rectangular ducts as well as fittings. Lindab has a line of components that consists of up to 75% recycled steel resulting in an environmental impact that is 70% lower in kg CO_2e emission than newly produced components from purely raw material. Components made with recycled steel have the same product properties (Lindab, 2023). However, this might entail additional investment costs since these components have a higher cost. This step also includes implementing DCV strategies.

4.3 Operational energy

In the energy balance of the building, lost energy due to transmission and infiltration through the building envelope is constant and therefore not included in the energy calculation (Petersson, 2018). The energy use related to the ventilation system occurs due to the heat losses through the system associated with heating the supply air to room temperature, in addition to the fan energy use. The energy requirement for heating the air is used for the heating coil (E_{HC}) is calculated according to Equation 4. (Warfvinge & Dahlblom, 2010)

$$E_{HC} = \rho \cdot c_p \cdot q_v \cdot (1 - \eta) \cdot t \cdot D_h \tag{4}$$

E_{HC} = Heating coil heating energy in Wh/year
ρ = Air density of 1.2 kg/m^3
c_p = Specific air heat capacity of 1000 J/(kg K)
q_v = Airflow in m^3/s
η = Energy efficiency of the heat exchanger
t = Fraction of annual operation hours
D_h = Degree hours in °Ch/year

Values for the different parameters included inS the equation above are taken from the description provided for AHU LA01 and LA02 in Table 6. The value for the degree hours was based on the location of the preschool being in the south of Sweden and equal to 85 600 h/year. (Warfvinge & Dahlblom, 2010) The simplification made for the previous equation to be valid was that the supply and room temperatures are equal.

The energy use for the fan (E_F) is calculated separately for the supply and exhaust system, affected by several factors with values provided by the AHU property description, and is defined by Equation 5 below. (Warfvinge & Dahlblom, 2010)

$$E_F = \frac{\Delta p \cdot q}{\eta_{fan}} \cdot t \tag{5}$$

E_F = Fan electricity in Wh/year
Δp = Pressure loss in Pa
q = Airflow in m^3/s
η_{fan} = Fan efficiency including the efficiency of the fan wheel, transmitter, and motor
t = Operation hours per year in h/year

The total energy use of the ventilation system is calculated by adding the energy needed for the heating coil, supply, and exhaust fan using Equation 6, below.

$$E_{tot} = E_{HC} + E_{F-supply} + E_{F-exhaust} \tag{6}$$

The operation hours are between 05:00 to 19:00, five days a week and since LA01 operates with a constant airflow, it is on during all operating hours and off otherwise. However, LA02 has a partial demand control that can be manually activated by a control panel and therefore operates with forced ventilation with the maximum airflow for five hours of the operation hours and the rest with the minimum airflow. The heating coil is also considered to only use energy during the winter months of the year assumed between October to April during operational hours resulting in a total of 28 weeks (SMHI, 2023). Since the efficiency of the rotary heat exchanger can be lowered by regulating the speed of the rotor during the summer and the plate heat exchanger has a bypass and can therefore be turned off during the summer, the operational hours for heating are only considered for the winter months. The resulting operation hours used in the calculation for the energy use for different components in the AHU are shown in Table 7, below.

Table 7. Operation hours for LA01 and LA02.

AHU	**LA01**		**LA02**			
Component	Fan	Heating coil	Fan		Heating coil	
			Min	Max	Min	Max
Operation time /(h/year)	3 640	1 960	2 340	1 300	1 160	800

4.4 Occupancy level

The parameter that can determine the possibility of installing a DCV or VAV system compared to a CAV system is dependent on the occupancy level. The occupancy level for this study was based on two methods being conducted interviews and measurements to get a broader perspective of the fluctuations of the occupancy level.

4.4.1 Interview

To establish an accurate evaluation of the occupancy level of the building, interviews with several staff members in Preschool B in Arlöv, the preschool in use with the same standard design of concept D, were conducted, since Preschool A is not yet in service. The questions aimed to acquire information regarding attendance, routines followed during the day, and how often certain rooms were used. The information acquired was utilized in creating an occupancy schedule that will be the basis for the ventilation system schedule with a varying airflow volume.

4.4.2 Measurement of occupancy rate

Conducting measurements to determine the occupancy level is mainly connected to the CO_2 concentration in indoor air compared to outdoor air. Parameters connected to indoor air quality including the temperature, relative humidity, and carbon dioxide concentration were taken using instrument EXTECH SD800. The measurement was performed by placing the instrument along the exhaust filter to record the carbon dioxide concentration in the exhaust air. A data logger was used for the readings with a recording interval of 5 minutes. The measurement period was for three days from 2024-03-13 at 10:00 to 2024-03-15 at 18:00. CO_2 concentration was also measured in outdoor air during the first and last day of measurements. The carbon dioxide production can be calculated using Equation 7. (Johansson, Bagge & Mjörnell, 2019)

$$C_p = (C_{in} - C_{out}) \cdot q \tag{7}$$

C_p = Carbon dioxide production in l/s
C_{in} = Carbon dioxide concentration in exhaust air in ppm
C_{out} = Carbon dioxide concentration in outdoor air in ppm
q = Ventilation airflow in l/s

Equation 8, below was used to calculate the actual number of persons that are in the building during the time of measurement during operational hours.

$$n = \frac{C_p}{c_p} \tag{8}$$

n = number of persons
C_p = Total carbon dioxide production in l/s
c_p = Carbon dioxide production per person in l/s

The average occupancy percentage was then calculated as a fraction of the actual number of people in the preschool calculated previously, divided by the designed number of people for the space. Values assumed for the carbon dioxide production per person for children and adults were based on an average calculated for Table 4 and Table 5 provided in the literature review. A combined value for the carbon dioxide production was calculated as an average assuming a ratio of adults to children equal to 1:3, matching their number distribution in reality. Table 8, shows these calculated values.

Table 8. Average carbon dioxide generation for children and adults and the combined value with a ratio of 1:3.

Average value	Children	Adults	Combined
CO_2 generation rate /(l/s)	0.0042	0.0116	0.0061

4.5 DCV design strategies

Based on the occupancy level the ventilation system can be adjusted by a reduction in size of some components to suit the newly designed ventilation airflow and the addition of components and technologies to operate as a DCV system.

4.5.1 Duct system

The duct system can be resized according to the adjusted designed airflow provided based on the occupancy level determined by the measurements and interviews. Ducts connected to the air terminals in the rooms are not resized to maintain the ability to supply the designed maximum airflow without any high noise production. Mainly main vertical and horizontal branch ducts were resized with the new maximum percentage of the designed total airflow.

The ventilation system was modelled in MagiCAD, a BIM solution for installation design, and MagiCAD was therefore used to resize the duct system by changing the airflow in air terminals, excluding those in areas that need to be supplied or exhausted with a constant airflow volume. Exhaust air terminals in wet areas such as bathrooms and the storage space at the entrance were not adjusted due to higher moisture and pollutant levels. These areas will be exhausted with the maximum constant airflow designed. The volume of air designated to these wet areas makes 16% of the maximum designed exhaust airflow volume. Only the storage space and electricity room will be supplied with the maximum constant airflow accounting for almost 6% of the maximum designed supply airflow volume. In addition to these constant airflow volumes supplied and extracted, a minimum of 0.35 l/s per m^2 was considered in the remaining spaces resulting in a percentage equal to 4% of the maximum designed airflow volume. However, since the minimum requirement in addition to the determined constant airflow is higher for the exhaust system, the minimum supply airflow volume is set to be equal to the exhaust to maintain a balanced system, resulting in a total of 20% of the maximum designed airflow.

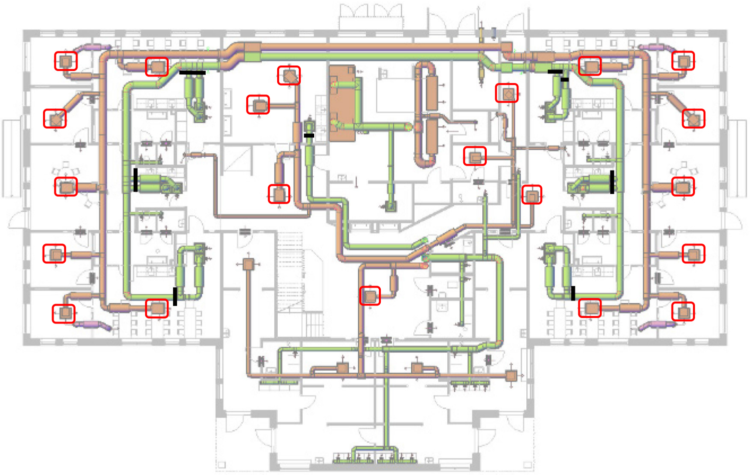
Resizing the duct system was performed by using the equal friction method available in MagiCAD where the maximum pressure drop is set to 1 Pa/m and the maximum velocity equal to 6 m/s. To ensure that the noise level does not exceed the recommended value of 30 dB, the air velocity in the ducts was maintained within the appropriate ranges according to Table 1. Balancing the system was also performed in MagiCAD to acquire the total pressure drop in the duct system for different airflow volumes used for further energy use calculations.

4.5.2 Additional Components

Modifying the system from a CAV into a DCV system requires technical additions and substitution. Almost all supply air terminals of the model RHKB from FläktGroup in the different departments and mutual spaces were substituted with active air terminals of the model ISQ and RAPH from Lindinvent and FläktGroup respectively depending on the connection duct size and airflow volume. The supply air terminals in the storage spaces at the entrance were not substituted because the space operates as a CAV system. The active air terminals come with an inbuilt CO_2 sensor connected to the flow damper programmed to regulate the airflow on demand. The noise level in air terminals was controlled to not exceed 30 dB by ensuring the airflow volume did not exceed the recommended maximum in the technical catalog of the product provided by the manufacturer.

With opting to supply active air terminals, flow dampers are required on the exhaust system to communicate with the supply air terminals and regulate the airflow to maintain pressure balance. Smart flow dampers of the model DCV-BLB were chosen from Lindinvent. In total 32 flow dampers were added to the system. Substituted supply air terminals and additional flow dampers are illustrated in Figure 13. In addition, a small modification to the layout has been made where a total of eight supply air terminals in the corridors with a supply airflow volume equal to 30 l/s were removed from both the first and second floor dividing their airflow on the other air terminals in the same area.

Floor 1



Floor 2

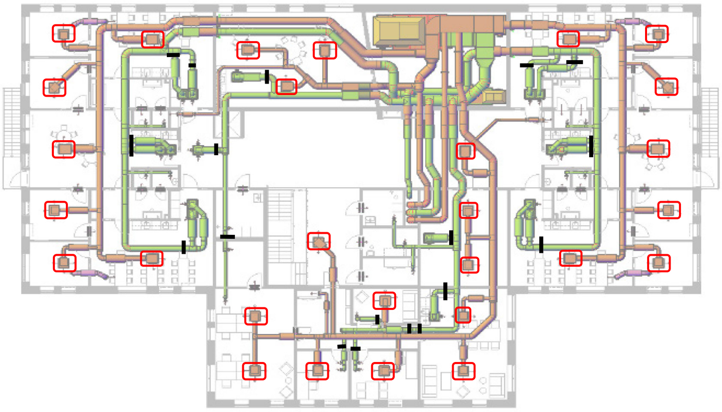


Figure 13. Illustration of substituted supply air terminals and added flow dampers.

4.5.3 Air handling unit

Based on the occupancy level deduced by the measurements and interviews the AHU was resized to match the newly designed airflow volume. The process of resizing was performed in the same method as for the base case which is using FläktGroup. Upon design, the new calculated pressure loss in the duct system was taken into consideration. Connected to the AHU is the roof hood and transition for air intake and exhaust which were also downsized to suit the reduced airflow requirements. Using the new values for the maximum air flow supplied, the same input data for both summer and winter, including dimensioned temperature, relative humidity, and requirements from standard EN 308, a new unit by FläktGroup was modeled.

4.6 LCA

The type of LCA conducted was conventional LCA and the goal was to determine and evaluate the environmental impact related to the life cycle phases of a CAV ventilation system and the alternative improved DCV system. The functional unit is a preschool with balanced mechanical ventilation ventilated based on the minimal airflow requirements being 7 l/s, per person and 0.35 l/s per m^2 maintaining an indoor temperature between 22 and 26°C during winter and summer respectively, expressed per m^2 for a lifespan of 50 years. The system boundary of the assessment was defined by the production and construction stages A1- A5, maintenance B2, Replacement B4, and operational energy use B6 for the use stages, see Figure 14. End of life phase was not taken into consideration in this assessment. The potential environmental impact per life cycle phase of the ventilation system considered is the global warming potential (GWP). More specifically GWP-total was considered for consistency and simplicity since not all EPDs report GWP-GHG and instead consider GWP-Fossil, GWP-Biogenic, and GWP-Luluc adding up to GWP-total.

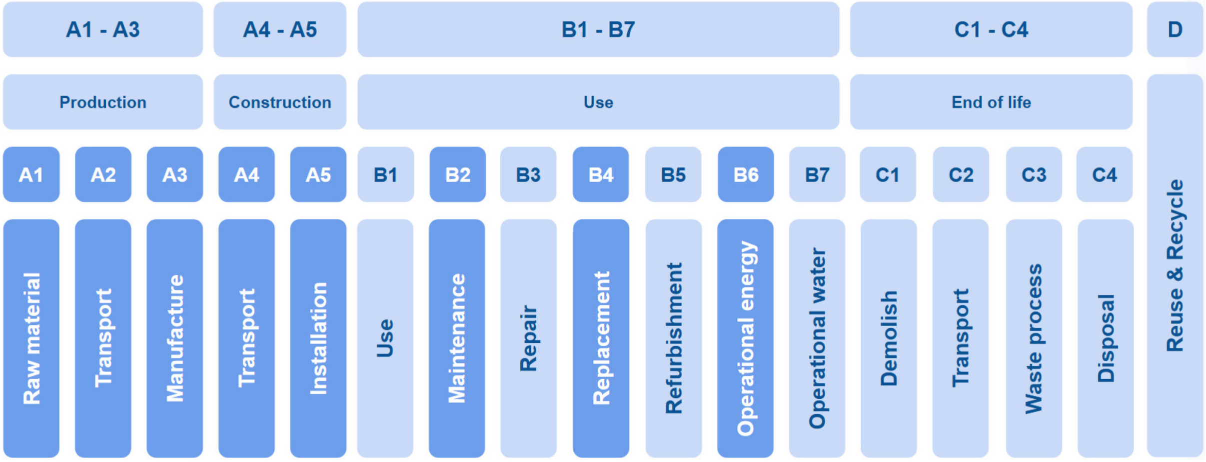


Figure 14. LCA stages included in the System boundary.

4.6.1 Stage A: Production & Construction

From the 3D model of the ventilation system modelled in MagiCAD, a bill of materials (BOM-list) that includes all the components of the ventilation system, their quantity, and product type was obtained. The environmental impact of these different components was primarily acquired from the EPDs provided by manufacturers mainly Lindab, FläktGroup, and Swegon. For components that lack an EPD, the environmental impact was manually calculated based on the product weight and material composition provided by the technical catalogue and building product declaration (BPD), multiplied by the individual raw material emission from a database provided by Boverket. Different components have different declared units for their environmental impact. Circular and rectangular ducts have a declared unit of 1 meter's length and 1 m^2 surface area respectively, while special products such as elbows, T-junctions, dampers, diffusers, silencers, and AHU are calculated per piece and have a declared unit of 1 kg.

4.6.2 Stage B: Use

Stage B2 involves maintaining and cleaning the building, including the impacts from stages A1-A5 of the products used. Filter replacement every year was considered a maintenance procedure because of its continuity. Stage B4 includes replacing building components if their lifespans are less than the building service life. (Skanska, 2019) The AHU has a lifespan of 25 years, based on the information provided by the contractor and manufacturer, which is less than the building service life the calculation is made for being 50 years. The impact from stages A1-A5 for the AHU was therefore additionally considered in stage B4 after 25 years when replacement takes place.

In the operational phase B6, the form of energy that was considered to supply the fans in the AHU was electricity based on the Swedish electricity mix, while the heating coil in the AHU is connected to the district heating. The base primary values for the emission factors used to calculate the operational energy use B6 phase were based on the generic values provided by Boverket being 0.037 and 0.056 kgCO_2e/kWh for electricity and district heating respectively.

4.6.3 Parametric analysis

The parametric study concerns the method for the calculation of the environmental impact due to operational energy use, stage B6. Different methodologies have different emission factor values for both district heating and electricity. The variation in the energy use for heating based on location was recalculated using corresponding degree hour values based on available data for cities on the same latitude, presented in Table 9 below. (Petersson, 2018)

Table 9. Chosen location for the parametric study and its respective degree hours.

Location	Hässleholm	Linköping	Stockholm
Degree hours /(°Ch/year)	85 600	86 900	108 000

The different emission factor values for district heating provided by different methods for B6 calculation were used to conduct a parametric study. These values vary depending on both method and location and were compiled in Table 10, based on a greater range of data provided by a previous study. (Hinsegård & Vitanc, 2023)

Table 10. Emission factors for district heating for the different locations based on the method chosen.

Method	**Emission factor /(kg CO_2e/kWh)**		
	Hässleholm	**Linköping**	**Stockholm**
Climate database by Boverket	0.056	0.056	0.056
NollCO2	0.060	0.060	0.060
EPD	0.036	0.011	0.015
Swedenergy	0.102	0.094	0.046

The parametric study also includes different emission factor values for electricity based on the same methods chosen for the district heating analysis however independent of the location.

Table 11, shows the values used for the parametric study regarding electricity, summarised from the same previous study (Hinsegård & Vitanc, 2023).

Table 11. Different emission factors for electricity based on the different methods chosen.

Method	**Emission factor /(kg CO_2e/kWh)**
Climate database by Boverket	0.037
EPD (Cogeneration)	0.014
NollCO2	0.022
Swedenergy, VMK	0.372

4.7 LCC

An LCC analysis was conducted for the traditional BATNEEC and BAT approach where the cost for material and energy was calculated separately but following the Net Present Value (NPV) method where future cash flows are discounted to a present value with regards to initial investment costs (A_1). (Chegg, u.d.)

To calculate the cost for the installed material Equation (9) was used. The interest rate was calculated as a nominal interest rate with a value of 4% (Sveriges Riksbank, 2024). The nominal price change (CPIF) was assumed to be 2.2% and the calculation period was set to be 50 years (Statistikmyndigheten, 2022). The calculation period was 50 years, but since the lifespan of the air handling unit is 25 years and the filter replacement occurs every year excluding the first and 26th year when a new AHU is installed, a reinvestment was needed. Reinvestment was also calculated according to Equation (9). The overall cost for the ventilation system as installed material was provided by the contractor, where the reinvestment cost was added. Further maintenance cost for workers was considered as a limitation in this study.

$$NPV_{Material} = Inital\ cost(1+g)^{N} \cdot (1+i)^{-N} \tag{9}$$

$NPV_{Material}$ = Net present value for installed material in SEK
g = Nominal rate of price change
i = Nominal interest rate

The cost for the operational energy use was calculated by using a geometric gradient according to Equation (10) and Equation (11). Values for the nominal interest rate and price change were the same for the operational phase cost calculation. The price for electricity is fixed equal to 1.2 SEK/kWh (E.on, 2024). The price for district heating is also fixed being 1.1 SEK/ kWh and both the electricity and heating include Value Added Tax (VAT) (E.on, 2024).

$$NPV_{Energy} = A_1\left(\frac{1-(1+g)^{N}\,(1+i)^{-N}}{i-g}\right) \tag{10}$$

$$A_1 = initial\ cost\ (1+g)^1 \tag{11}$$

NPV_{Energy} = Net present value for energy use in SEK
A_1 = First year cost in SEK
g = Nominal rate of price change
i = Nominal interest rate

The total NPV is the summation of expenses for the installed material including the initial added to the reinvestment cost and the operational energy cost, see Equation (12), below.

$$NPV_{Total} = NPV_{Material} + NPV_{Energy} \tag{12}$$

To better understand how different parameters have an impact on the total NPV value and payback time for the different cases investigated, a sensitivity analysis was conducted. The sensitivity analysis includes the energy prices for one scenario and the interest rate in another as the changing parameters while having all other parameters fixed. The values are set to be 50% higher and lower than the current value, resulting in a nominal interest rate of 2% and 6%, an electricity price change of 0.7 and 0.6 (SEK/kWh), and a price change for district heating equal to 2 and 1.7 (SEK / kWh).

Payback time was calculated considering the year savings become more than expenses. Where the expenses consist of the initial investment cost for material and savings the difference between the energy use cost for the traditional approach and the improved case, and the NPV_{saving} is the difference between them.

4.8 ILCA

The integrated life cycle assessment was conducted for all cases involving the traditional, BATNEEC and BAT approach. Within the LCA part, the process of weighting and normalization was not performed since only one potential environmental category was considered, which is GWP. To calculate the environmental score per case, the evaluated impact due to installed material and operational energy use was added. Regarding LCC, the economic score per case was also calculated by the addition of the investment cost for installed material, and operational energy cost. To calculate the environmental and economic performance separately, internal normalization based on the total of all the scores was performed. The environmental and economic weighting factors were set between 25, 50, and 75% each adding up to 100%. The overall performance of the different cases was calculated using the following Equations, 13, 14, and 15. (Deiso, 2022)

$$Environemntal\ performance = Environmental\ weighting\ factor\ \left(\frac{Environmental\ score}{Total\ Environmental\ score}\right) \tag{13}$$

$$Economic\ performance = Economic\ weighting\ factor\ \left(\frac{Economic\ score}{Total\ Economic\ score}\right) \tag{14}$$

$$Overall\ Performance = Environmental\ performance + Economic\ performance \tag{15}$$

5 Results and analysis

5.1 Energy efficient ventilation

To determine the possibility for the implementation of a DCV system, the occupancy level dictates the newly designed ventilation airflow affecting the design strategies applied to the system. With the system connected to LA02 designated for only the kitchen area and already operating as a manually controlled DCV system, system LA01 has more potential for a transformation into a DCV system.

5.1.1 Occupancy level

Based on the information provided from the conducted interviews, 120 children are registered which is the number the building is initially designed for. However, the average attendance over the year does not exceed 90 children on Monday to Thursday and 70 on Fridays. The number of staff members is 22 which is somehow constant over the year because any shortage of staff is substituted upon need. The cleaning and kitchen staff consist of one person respectively. Table 12, is a compilation of the provided information made into an occupancy schedule describing the number of children and staff inside the preschool during work hours based on their daily routines. The occupancy schedule is the same for Monday to Thursday but differs on Friday.

Table 12. Number of children and staff during occupied hours.

Monday - Thursday												
Time	**06 - 07**	**07 - 08**	**08 - 09**	**09 -10**	**10 - 11**	**11 - 12**	**12 - 13**	**13 - 14**	**14 - 15**	**15 - 16**	**16 - 17**	**17 - 18**
Children	45	90	45		90					0		45
Staff	11	22	11		22					0		11
Cleaning	1											
Kitchen	0	1									0	
Friday												
Time	**06 - 07**	**07 - 08**	**08 - 09**	**09 -10**	**10 - 11**	**11 - 12**	**12 - 13**	**13 - 14**	**14 - 15**	**15 - 16**	**16 - 17**	**17 - 18**
Children	35	70								0		35
Staff	11	22								0		11
Cleaning	1											
Kitchen	0	1									0	

Based on the occupancy schedule a ventilation schedule that describes the percentage of provided airflow volume relative to the total designed airflow volume during the ventilation hours was created, see Table 13. The ventilation schedule mainly matches the occupancy schedule for the children and teachers since they make up the largest percentage of the occupants.

Table 13. Ventilation schedule based on occupancy schedule from interviews.

Monday – Thursday														
Time	**05-06**	**06-07**	**07-08**	**08-09**	**09-10**	**10-11**	**11-12**	**12-13**	**13-14**	**14-15**	**15-16**	**16-17**	**17-18**	**18-19**
Airflow	20%	40%	80%	40%		80%					20%		40%	20%
Friday														
Time	**05-06**	**06-07**	**07-08**	**08-09**	**09-10**	**10-11**	**11-12**	**12-13**	**13-14**	**14-15**	**15-16**	**16-17**	**17-18**	**18-19**
Airflow	20%	33%	65%								20%		33%	20%

At zero occupancy, 20% of the designed airflow volume includes the constant airflow requirements in certain spaces and the minimum airflow requirements in other spaces. At 100% occupancy, the airflow is at 80% which is a factor relative to the designed maximum, stemming from the fact that the attendance includes 90 children and 24 staff members of the total designed number 144 persons. The airflow percentages on Friday are less because of the reduced number of children. A calculated average value for the ventilation schedule is 50% relative to the total designed airflow volume.

According to the measurements, the maximum CO_2 concentration during the days of measurement occurred on Thursday at 11:00 and Friday at 13:00 with values equal to 509 and 479 ppm respectively. The CO_2 concentration in outdoor air shows little variation and has an average of 386 ppm. These measured values result in a CO_2 production calculated using Equation 7, as follows.

Thursday: $C_p = \frac{(509-386)}{10^6} \cdot 4605\ l/s = 0.5664\ l/s$

Friday: $C_p = \frac{(479-386)}{10^6} \cdot 4605\ l/s = 0.4283\ l/s$

Considering that the children and adults are divided into 75% and 25% of the occupants, an average combined CO_2 generation rate value was used together with Equation 7, to calculate the maximum number of occupants in the preschool during the days of measurements.

Thursday: $n = \frac{0.5664}{0.0061} = 94$ persons

Friday: $n = \frac{0.4283}{0.0061} = 70$ persons

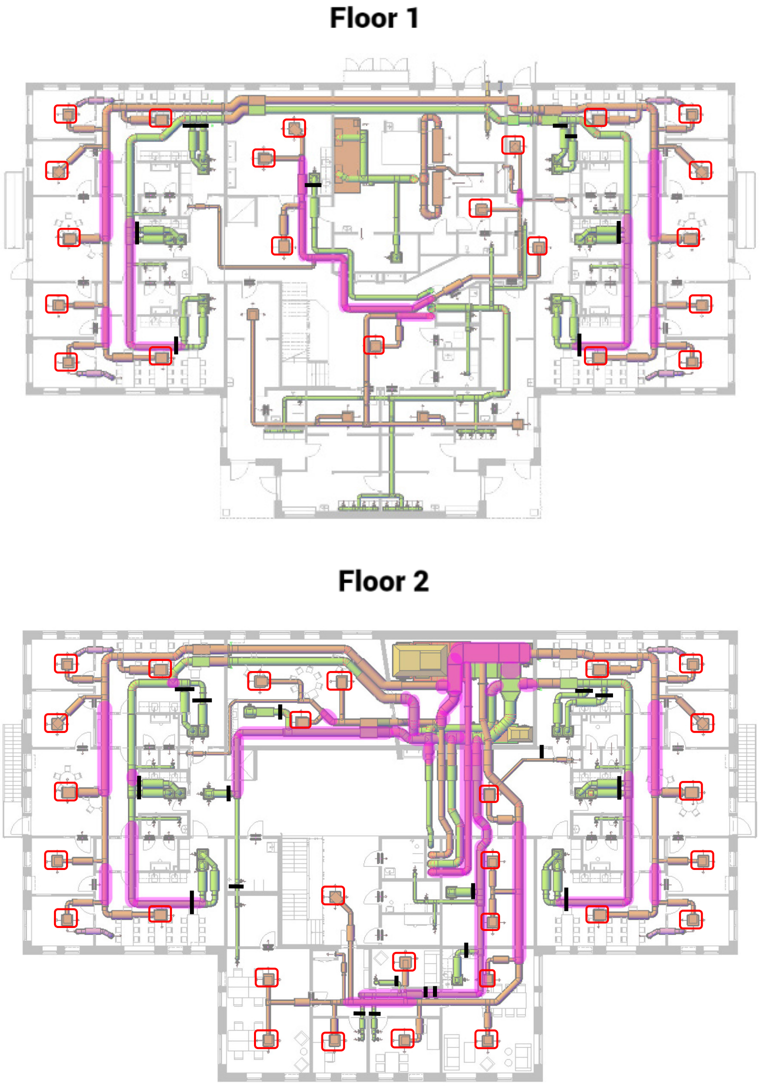
To complement the measured values, general information provided by the interviews, such as having the same number of children Monday to Thursday in comparison to Friday, was taken into consideration. With a maximum number of occupants equal to 94 and 70 people on Thursday and Friday respectively, the same calculation method above was used to deduce a ventilation schedule that describes the percentage of provided airflow volume relative to the maximum designed airflow volume during the ventilation hours, see Table 14. A calculated average value for the ventilation schedule created based on the measurements is 40% of the maximum airflow.

Table 14.Ventilation schedule during occupied hours based on measured values.

Monday – Thursday														
Time	**05-06**	**06-07**	**07-08**	**08-09**	**09-10**	**10-11**	**11-12**	**12-13**	**13-14**	**14-15**	**15-16**	**16-17**	**17-18**	**18-19**
Airflow	20%		33%		40%	65%				40%	33%		20%	
Friday														
Time	**05-06**	**06-07**	**07-08**	**08-09**	**09-10**	**10-11**	**11-12**	**12-13**	**13-14**	**14-15**	**15-16**	**16-17**	**17-18**	**18-19**
Airflow	20%		33%	40%	50%						40%	33%	20%	

5.1.2 DCV strategies

Based on the results received in the occupancy study, the duct system was modified by reducing the size of some ducts to fit 80% of the designed total airflow being 3700 l/s. Figure gör15 illustrates the changes made to the ventilation system where the highlighted purple parts of the duct system were reduced by one or two sizes, the air terminals that were substituted with active air terminals are encircled in red and the position of flow damper additions in exhaust ducts are marked in black.



Floor 1

Floor 2

Figure gör15. Modified ventilation system with new active air terminals, flow dampers, and duct sizes.

Using the new values for the designed airflow, the same input data for both summer and winter and requirements from standard EN 308, a new unit by FläktGroup was modeled. In an attempt to not exceed the SFP_v value set by Boverket being 1.5 kW/(m^3/s), it was not possible to downsize the AHU and therefore model eQ Prime Side – 050 with the same original size but with smaller fans and adjusted lamella on the heat recovery wheel was chosen, see Figure 16. Related to the resizing of the AHU, the roof hood and transition were also downsized by one size resulting in a lower mass of steel.

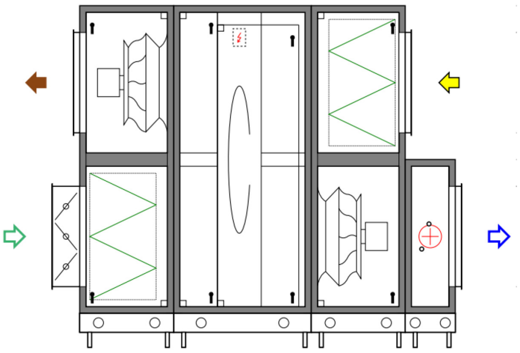


Figure 16. Downsized AHU modeled by FläktGroup.

The new SFP$_v$ decreased to 1.28 kW/(m^3/s), which represents an 11% reduction and an improvement over the previous value. The new input data for the revised model is presented in Table 15.

Table 15. Input data for the new AHU.

Description	**LA01**
Efficiency of dry heat exchanger /%	81
Airflow – supply ; exhaust /(l/s)	3684 ; 3684
Pressure drop – supply ; exhaust /Pa	368 ; 375
Fan efficiency – supply ; exhaust /%	66 ; 66

5.1.3 Operational energy use

The energy used during operational hours for the ventilation systems connected to LA01 and LA02 is shown in Table 16, below. A detailed calculation of the operational energy use for both systems can be seen in Appendix A. The energy use for LA02 was divided into a minimum and maximum based on the airflow during operational hours. The total energy use per year for system LA01 is significantly higher than LA02.

Table 16. Total energy use per year for LA01 and LA02 for traditional case.

Energy use /(kWh/year)		**LA01**	**LA02**	
			Min airflow	Max airflow
Heating coil		19 500	430	1 000
Fan	Supply	11 300	250	560
	Exhaust	11 400	230	540
Total		**42 200**	**3 010**	

Based on the ventilation schedule in Table 13, the operational energy use for system LA01 was calculated taking into account the variation in pressure drop in the system caused by the different airflow volumes being supplied and extracted into different spaces. The detailed calculation can be seen in Appendix B and a compilation of it is presented in Table 17 below. The percentages with a higher energy use depend on the longer duration depending on the ventilation schedule provided in Table 13.

Table 17. Energy use for heating coil and fan for different airflows based on occupancy level provided by interviews.

Energy use /(kWh/year)		**Designed airflow relative to the max**				
		80%	**65%**	**40%**	**33%**	**20%**
Heating coil		5 510	1 500	1 900	200	811
Fan	**Supply**	2 560	613	685	70	289
	Exhaust	2 610	612	702	71	297
Total		**18 400**				

The operational energy use was calculated for the ventilation schedule seen in Table 14 for system LA01 based on the measurements conducted resulting in different airflows being supplied throughout the day, hence leading to different pressure drops, seen in Appendix C. Compilation of the energy use is presented in Table 18, below. The energy use for 40% and 33% is higher than 50% energy use due to longer operational hours, according to the ventilation schedule provided in Table 14.

Table 18. Energy use for heating coil and fan for different airflows based on occupancy level provided by measured values.

Energy use /(kWh/year)		**Designed airflow relative to the max**				
		65%	**50%**	**40%**	**33%**	**20%**
Heating coil		2 990	862	1 150	1 700	811
Fan	**Supply**	1 230	333	428	625	289
	Exhaust	1 220	338	438	640	297
Total		**13 400**				

Operational energy use was also calculated for the average value of 50% and 40% for system LA01 based on the ventilation schedule provided by interviews and measurements respectively, see detailed calculation in Appendix D. The energy use was also calculated for a number of percentages representing the average value for the ventilation schedule based on occupancy level. These percentages were determined based on findings in previous studies on the topic of occupancy level within the range of 70% to 20% with an increment of 10% between. Table 19, shows a parametric analysis of the variation in the design ventilation airflow based on an average value for the occupancy level.

Table 19. Energy use for different average airflow volumes based on an average occupancy level.

Energy use /(kWh/year)	**Average designed ventilation airflow**					
	70%	**60%**	**50%**	**40%**	**30%**	**20%**
Heating coil	14 100	12 100	10 100	8 040	6 040	2 840
Fan	11 800	9 700	7 630	6 070	4 450	2 050
Total	**25 900**	**21 800**	**17 700**	**14 100**	**10 500**	**4 880**

It is worth mentioning that the results for having a ventilation schedule at a constant 50% and 40% in comparison to the variable ventilation schedule created previously based on conducted interviews and measurements show an insignificant difference in the values for the energy use calculated. This implies an adequate level of accuracy for the rest of the percentages investigated.

5.2 LCA - Stage A: Production & Construction

An LCA calculation for stages A1-A5 was conducted for the different alternatives including the traditional approach, BATNEEC and BAT.

5.2.1 Traditional

The traditional approach is considered to be the base case on which adjustments and improvements are based. Figure 17 shows the potential environmental impact category GWP for the different A stages for a calculation period of 50 years. The production stage A1-A3 has the most significant impact, accounting for almost 94% of the total, see detailed calculation in Appendix E.

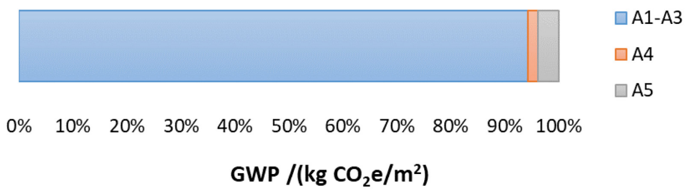


Figure 17. GWP due to production (A1-A3) and construction (A4-A5) for the traditional level.

GWP for stages A1-A5 is also calculated separately for systems connected to LA01 and LA02, see Table 20. According to the results system, LA02 has a lower total amount of kg CO_2e than LA01 but a higher amount of kg CO_2e per gross floor area (GFA). This is because the emissions are concentrated over a smaller area resulting in a higher intensity of emissions per unit area.

Table 20. GWP for A1-A5 for LA01 and LA02 over a calculation period of 50 years for the traditional level.

A1-A5	System		
	LA01	LA02	Both
GWP /(kg CO_2e /50 years)	36 200	6 500	42 700
GWP /(kg CO_2e /50 years/m^2)	**20.5**	**81.2**	**23.1**

The ventilation system was divided into sub-sections to identify the component group with the most significant percentage of the total environmental impact for the production and construction stages A1-A5. Figure 18, shows the percentage contribution of the subcomponents in both systems.

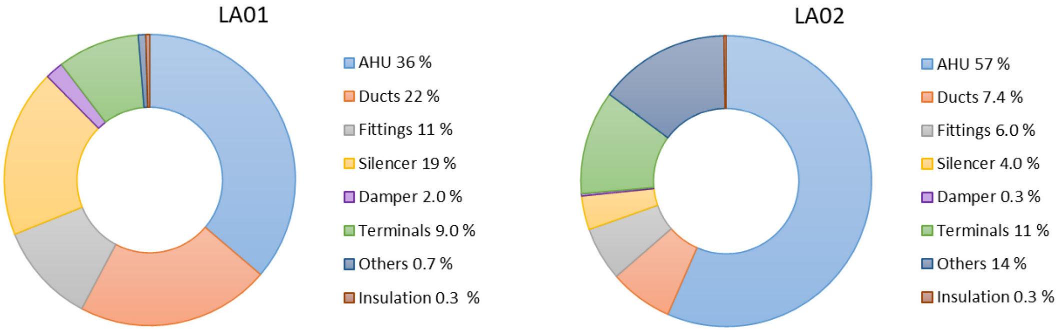


Figure 18. Percentage of the total GWP for stages A1-A5 the subcomponents account for in traditional level.

In both systems, the AHU is the largest contributor to the total CO_2 emissions. The AHU has the most significant impact because it serves as the central component in the ventilation system, responsible for managing airflow distribution and climate control. It requires substantial material usage which contributes to its significant environmental footprint compared to other components in the system. The duct system is the second largest subcomponent accounting for the total environmental impact including both ducts and fittings in system LA01. Category others in LA02 include the extract air cabinet in the kitchen which is a component with a large steel mass leading to the second highest percentage.

5.2.2 BATNEEC

This approach in LFM30's climate staircase focuses on ensuring that the implemented measures cost is effective. With the potential environmental impact for system LA02 left unchanged, the recalculated value for a DCV system for system LA01 is shown in Table 21. The calculation takes into account the duct size reduction, the removal of some supply air terminal devices, the substitution of supply air terminals with active ones, the addition of flow dampers, and the new AHU.

Table 21.GWP for A1-A5 for LA01 and LA02 over a calculation period of 50 years for the BATNEEC approach.

A1-A5	System		
	LA01	LA02	Both
GWP /(kg CO_2e /50 years)	35 500	6 500	42 000
GWP /(kg CO_2e /50 years/m^2)	**20.0**	**81.2**	**22.7**

Figure 19, shows the percentage of the environmental impact for stages A1-A5 the subcomponents account for, suggesting a redistribution within the system. The environmental impact due to LA02 was left unchanged considering that the system was not adjusted, see detailed calculation in Appendix E.

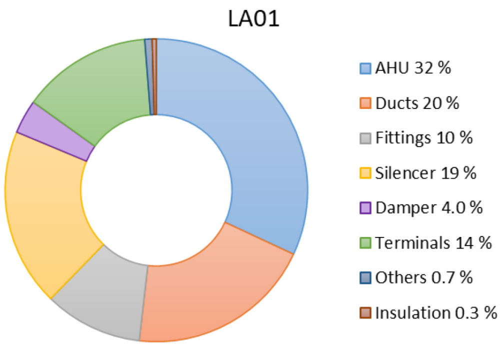


Figure 19. Percentage of the total GWP for stages A1-A5 the subcomponents account for in BATNEEC level.

The AHU is still the largest contributor to the total CO_2 emissions in system LA01, however, the percentage of the total impact due to the duct system and AHU has been reduced by 4% and 2% due to the size reduction. On the other hand, the percentage of the total impact the air terminal and damper accounts for has increased by 5% and 2% due to the addition of new flow dampers and active air terminals that have a higher environmental impact per item. The results show an insignificant reduction nor addition to the total environmental impact due to installed material in comparison to the traditional approach with the reduction due to ducts being compensated by the increase due to dampers and air terminals.

5.2.3 BAT

Considering that this step does not have a restriction regarding cost, it is a combination of having a DCV ventilation system and the use of recycled steel for the duct system. This modification only applies to the production and construction stage and does not affect the operational energy and the potential environmental impact caused by it. GWP for stages A1-A5 was calculated separately for systems LA01 and LA02, see Table 22. Both systems show a significant reduction in the total environmental impact and system LA02 still has a higher amount of kg CO_2e per GFA in comparison to LA01.

Table 22. GWP for LA01 and LA02 over a calculation period of 50 years for the BAT approach.

A1-A5	**System**		
	LA01	**LA02**	**Both**
GWP /(kg CO_2e /50 years)	27 900	5 900	33 800
GWP /(kg CO_2e /50 years/m^2)	**15.8**	**73.8**	**18.3**

Figure 20, shows the GWP impact distribution between the different subcomponents for systems LA01 and LA02, see detailed calculation in Appendix E.

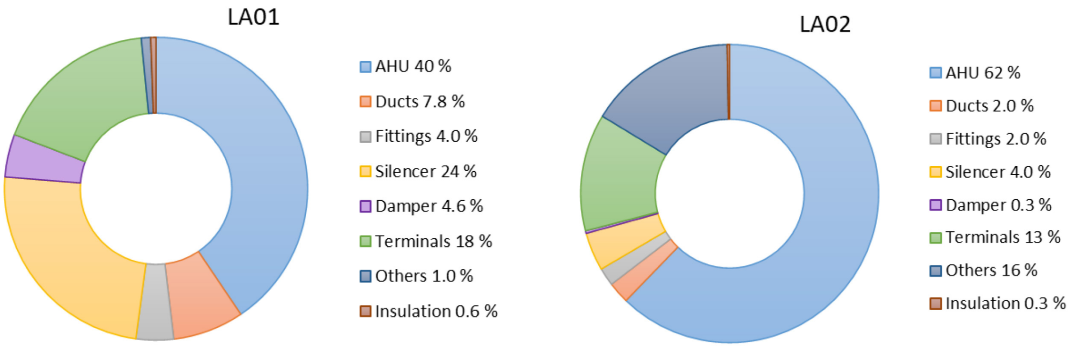


Figure 20. Percentage of the total GWP for stages A1-A5 the subcomponents account for in BAT level.

The percentage that the AHU accounts for has increased for both systems however not because its impact has increased in amount kg CO_2e but because the total environmental impact has been significantly reduced making it account for a larger portion. the percentage of the total impact the ducts and fittings account for has decreased significantly when using recycled steel. The percentage of the total of some subcomponents such as insulation and others has increased however their impact in kg CO_2e was unchanged.

5.3 LCA - Stage B: Use

An environmental impact calculation for B2, B4, and B6 under the usage stage of the building was conducted for the different alternatives including the traditional approach, consisting of a CAV system, and the BATNNEC and BAT approach, consisting of a DCV system.

5.3.1 Traditional

GWP for stages B2 and B4 calculated for systems connected to LA01 and LA02 can be seen in Table 23, and Table 24, respectively. Stage B2 consists of the replacement of 48 filters during the building life service of 50 years, excluding the first year and the 26th where a new AHU is installed including a new filter. For simplicity, stage B4 only includes the replacement of the entire AHU at once instead of the replacement of components within it on different occasions.

Table 23. GWP for Maintenance (B2) over a calculation period of 50 years for the traditional approach.

B2	**System**		
	LA01	**LA02**	**Both**
GWP /(kg CO_2e /50 years)	1 890	1 620	3 510
GWP /(kg CO_2e /50 years/m^2)	**1.00**	**20.3**	**1.90**

Table 24. GWP for Replacement (B4) over a calculation period of 50 years for the traditional approach.

B4	**System**		
	LA01	**LA02**	**Both**
GWP /(kg CO_2e /50 years)	13 100	3 680	16 800
GWP /(kg CO_2e /50 years/m^2)	**7.40**	**46.0**	**9.10**

GWP for stage B6 was calculated separately for systems LA01 and LA02 for 50 years of operation, see Table 25. System LA02 has a lower total amount of kg CO_2e than LA01 but a higher amount of kg CO_2e per gross floor area (GFA) for the same reason of having the impact concentrated over a smaller floor area.

Table 25.GWP impact for the operational stage (B6) over a calculation period of 50 years for the traditional approach.

B6	**System**		
	LA01	**LA02**	**Both**
	Electricity		
GWP /(kg CO_2e /50 years)	42 000	3 000	45 000
GWP /(kg CO_2e /50 years/m^2)	**23.5**	**37.5**	**24.5**
	District Heating		
GWP /(kg CO_2e /50 years)	54 500	4 000	58 500
GWP /(kg CO_2e /50 years/m^2)	**31.0**	**50.0**	**31.5**
	Total		
GWP /(kg CO_2e /50 years/m^2)	**54.5**	**87.5**	**56.0**

In 50 years the potential environmental impact GWP for the operational stage becomes 165% and 7% greater than the installed material for systems LA01 and LA02 respectively. The percentage for LA01 is significantly lower at 7% due to the already high impact per gross floor and the low amount of total energy use.

5.3.2 BATNEEC & BAT

This level was based on the occupancy level provided by the interviews and the measurements with system LA01 resized and redesigned to operate as a DCV system. The environmental impact due to stage B2 accounting for filter replacement was the same for this system as for the traditional approach, since the size of the filter did not change with the new AHU design. However, since the total weight of the AHU has changed, GWP for stage B4 was recalculated for system LA01, see Table 26. The impact due to stage B4 has shown a reduction of 15% for system LA01 and thus the total due to the reduced weight of the AHU.

Table 26. GWP for Replacement (B4) over a calculation period of 50 years for BATNEEC and BAT approach.

B4	System		
	LA01	LA02	Both
GWP /(kg CO_2e /50 years)	11 300	3 680	15 000
GWP /(kg CO_2e /50 years /m^2)	**6.40**	**46.0**	**8.10**

The potential environmental impact, GWP for stage B6 was calculated for the new DCV system LA01 based on the energy use calculated for the ventilation schedule created in accordance with the interviews, see Table 27. The impact due to operational energy use is still higher than the installed material in 50 years but was significantly decreased by 55% and 47% for systems LA01 and LA02.

Table 27. GWP for operational stage (B6) over 50 years for BATNEEC and BAT approach based on interviews.

B6		System		
		LA01	LA02	Both
GWP /(kg CO_2e /50 years/m^2)	Electricity	9.00	37.5	10.0
	Heating	15.5	50.0	17.0
	Total	**24.5**	**87.5**	**27.0**

The potential environmental impact, GWP for stage B6 was calculated for the new DCV system LA01 for different operational periods based on measured values, shown in Table 28. The environmental impact due to operational energy use for LA02 was unchanged but became 67% lower for system LA01 compared to the traditional approach. The impact due to B6 became lower for system LA01 than for installed material after 50 years but is still higher for system LA02.

Table 28. GWP for operational stage (B6) over 50 years for BATNEEC and BAT approach based on measurements.

B6		System		
		LA01	LA02	Both
GWP /(kg CO_2e /50 years/m^2)	Electricity	6.00	37.5	7.50
	Heating	12.0	50.0	13.5
	Total	**18.0**	**87.5**	**21.0**

GWP for stage B6 for the different average designed ventilation airflow based on previous studies and findings in this study for system LA01 are shown in Table 29. The results indicate a significant reduction in the environmental impact due to the operational energy use by having a lower average occupancy level.

Table 29. GWP for operational stage (B6) over 50 years based on different average occupancy.

B6	Average designed ventilation airflow					
	70%	60%	50%	40%	30%	20%
GWP /(kg CO_2e /50 years)	59 100	49 500	40 100	31 900	23 600	11 000
GWP /(kg CO_2e /50 years/m^2)	33.0	28.0	22.6	18.0	13.4	6.2

5.3.3 Parametric analysis

The parametric analysis was performed on the traditional approach being a CAV system and the BATNEEC and BAT approach including a DCV system for an average occupancy of 70%, 50%, 40%, and 20% based on the findings of this study and previous studies to establish an understanding of how these different methods can affect the energy use results. Energy use for heating recalculated considering location includes both systems LA01 and LA02, see Table 30.

Table 30. Total energy use calculated for different average occupancy based on locations.

Location	Energy use – Heating /(kWh/year)				
	Traditional	DCV : 70%	DCV : 50%	DCV : 40%	DCV : 20%
Hässleholm	20 900	15 500	11 400	8 940	4 270
Linköping	21 200	15 800	11 700	9 630	4 350
Stockholm	26 400	19 600	14 500	12 000	5 400

Figure 21, shows the environmental impact due to the operational heating energy use in stage B6 considering different emission factors for district heating based on different methods. Swedenergy indicates the highest impact while EPD is the lowest, due to Swedenergy not considering renewable resources for their energy production. With the heating energy demand increasing with latitude the amount of CO_2e emission increases accordingly.

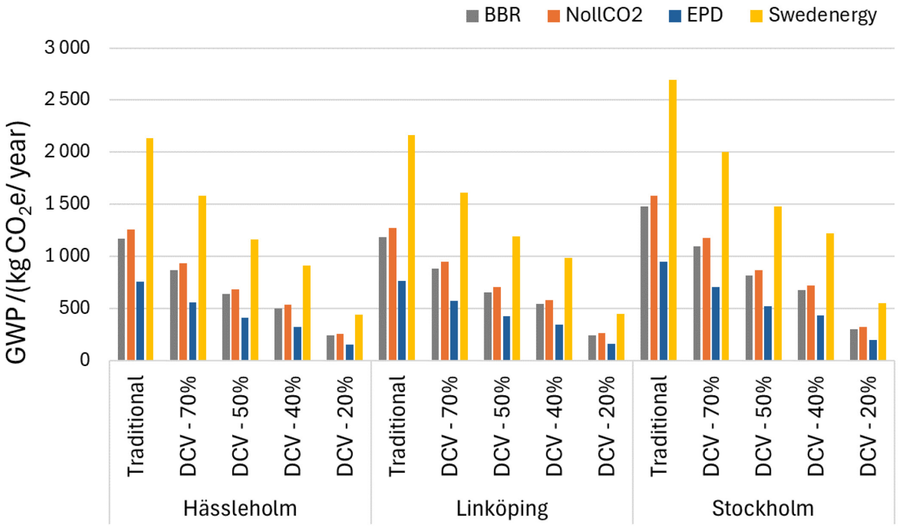


Figure 21. GWP for district heating based on different methods and locations.

Energy use for the electricity to the fan calculated for systems LA01 and LA02 together is not based on locations and can only be affected by which method is considered, see Table 31.

Table 31. Electricity use for different occupancy levels based on different methods.

Case	Traditional	DCV : 70%	DCV : 50%	DCV : 40%	DCV : 20%
Electricity /(kWh/year)	24 300	13 400	8 630	6 040	3 600

Figure 22, shows the environmental impact due to the operational energy use in stage B6 considering different emission factors for electricity based on different methods. Swedenergy indicates the highest impact with a significant difference compared to the other emission factor values, while generic data from NollCO2 is the lowest.

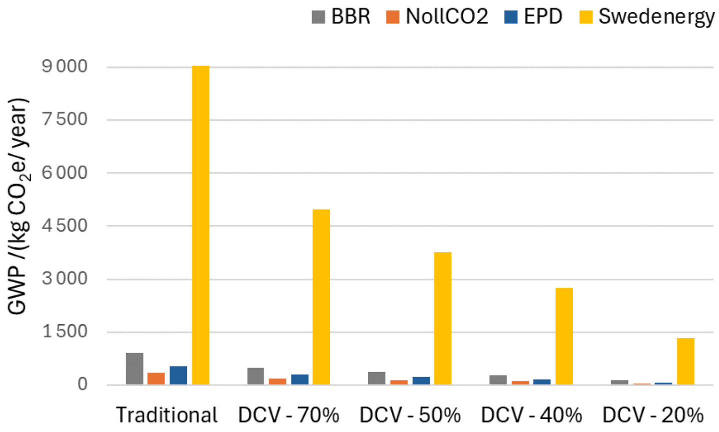


Figure 22. GWP for electricity based on different methods.

Figure 23, is a combination of both emission factors for district heating and electricity for the different methods taking into consideration the three different locations. Swedenergy still indicates the highest environmental impact which is related to the fact that the emission factor values do not include renewable energy sources. EPD shows the lowest environmental impact for having the lowest emission factor for district heating and an emission factor value relatively close to NollCO2 for electricity.

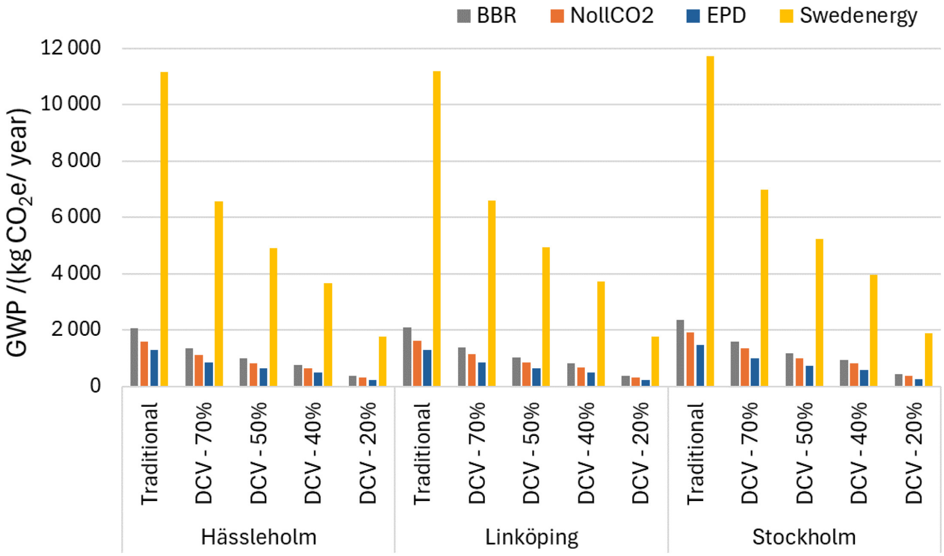


Figure 23. GWP for the total energy use based on different methods and locations for all cases investigated.

5.4 LCA – Stage A & B

Comparing the previous approaches Figure 24 shows the difference in the amount of kg CO_2e emission per component group between the Traditional, BATNEEC, and BAT levels, for the production and construction stage A1-A5 for both systems together for a period of 50 years.

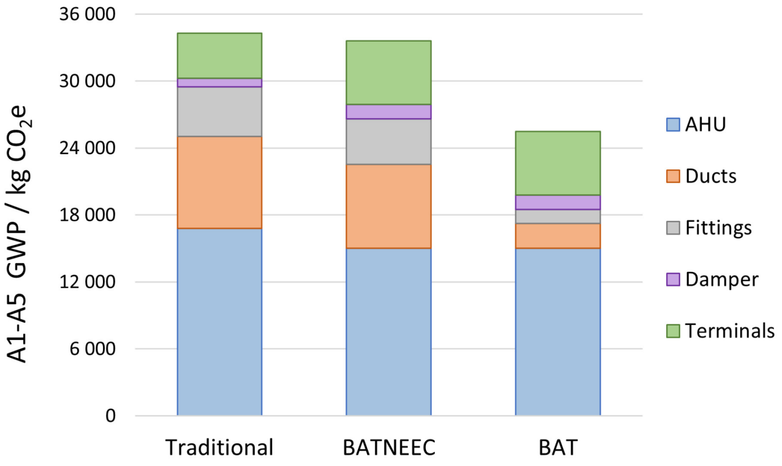


Figure 24. Compilation of the GWP distribution for all three approaches.

The reduction in the environmental impact attributed to the AHU and duct system is notable in both the BATNEEC and BAT alternatives due to the implementation of a DCV system which allowed for an AHU model that has a lower mass. The decrease in the environmental impact due to the duct system from the traditional to BATNEEC approach is equal to 10% while being a more substantial reduction when transitioning from the traditional to BAT approach, equal to 73%. Overall, the implementation of a DCV system and the integration of recycled materials represent strategic measures that contribute to a substantial reduction in the carbon footprint, particularly in terms of installed material.

Figure 25, is a compilation of the environmental impact due to the use stage, where the emission and savings for a period of 50 years in kg CO_2e/m^2 for the different operational ventilation schedules based on occupancy level are shown.

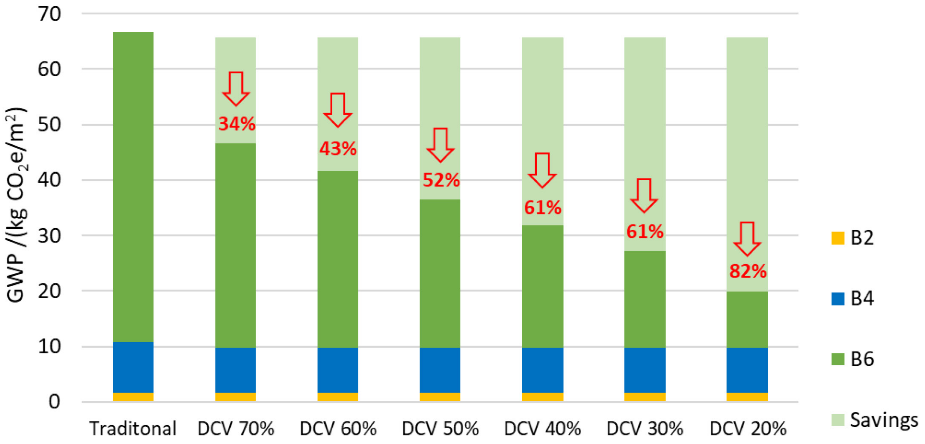


Figure 25. GWP impact for stage B for all cases.

The implementation of a DCV system shows a significant reduction in the environmental impact due to the operational energy use stage B6 with a percentage that shows to be complimentary to the percentage the DCV system operates at.

Figure 26, shows the environmental impact due to stages A and B in relation to one another, of the ventilation system in the different cases investigated.

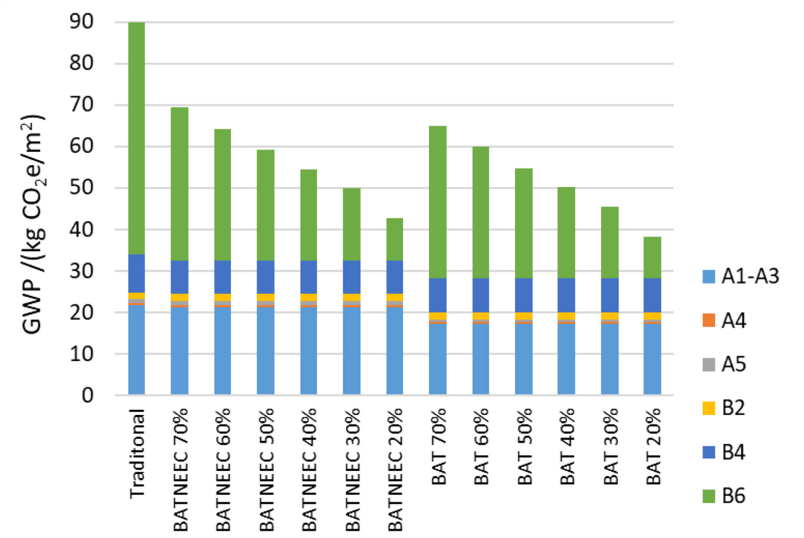


Figure 26. GWP for stages A and B for all cases.

The figure shows that the traditional approach has the highest total environmental impact from both stages A and B. Implementing strategies such as the DCV system and using recycled steel have shown a great improvement and reduction in the total environmental impact for these cases. However, these strategies implemented indicate that a reduction in stage A does not necessarily result in a reduction in stage B, and therefore they are not directly proportional or related. In the case of the implementation of the DCV system, the impact due to stage A1-A5 stayed relatively the same, because the removal and addition of components was evened out, however resulted in a notable reduction in the operational phase under B6. On the other hand, using recycled steel for the duct system has only resulted in a reduction in stages A1-A5 and not affected stage B6. The results also highlight the fact that stages A4, A5, and B2 have a relatively insignificant impact compared to other stages under the life cycle of the system. Which stage has the most significant percentage of the total environmental impact the system accounts for depends on the case. For the traditional case the impact due to the use stage B has a higher percentage due to a high operational energy use, while BATNEEC with a DCV system operating with an average of 20% has an impact due to stage B and A that are almost equal to one another.

5.5 LCC

The initial investment cost for installed material calculated as an NPV including the yearly filter replacement considered as maintenance and AHU replacement of both LA01 and LA02 after 25 years, calculated for 50 years is shown in Table 32. These cases have a nominal interest rate of 4% and a nominal price change of 2.2%.

Table 32. Total cost with consideration of maintenance cost for traditional, BATNEEC, and BAT approach.

Cost /SEK	**Case**		
	Traditional	**BATNEEC**	**BAT**
Initial investment	2 960 000	3 730 000	3 890 000
Reinvestment (AHU + Filter)	379 000	367 000	367 000
Total	3 340 000	4 100 000	4 260 000

The operational cost for energy use for the traditional ventilation system operating as a CAV system and the improved case with a DCV system operating at different occupancy levels, calculated for a period of 50 years is shown in Table 33. The value for the nominal interest rate and price change considered for these cases was 4% respective 2.2%. Savings were calculated as a percentage in relation to the traditional base case.

Table 33. The operational energy use cost for different average occupancy and their respective savings.

Case	**Traditional**	**DCV 70%**	**DCV 60%**	**DCV 50%**	**DCV 40%**	**DCV 30%**	**DCV 20%**
Energy cost /SEK	1 810 000	1 140 000	980 000	820 000	670 000	531 000	311 000
Savings		37%	46%	55%	63%	71%	83%

Total NPV including both investment for installed material and operational energy use cost for the combination of previous cases is represented in Figure 27, below.

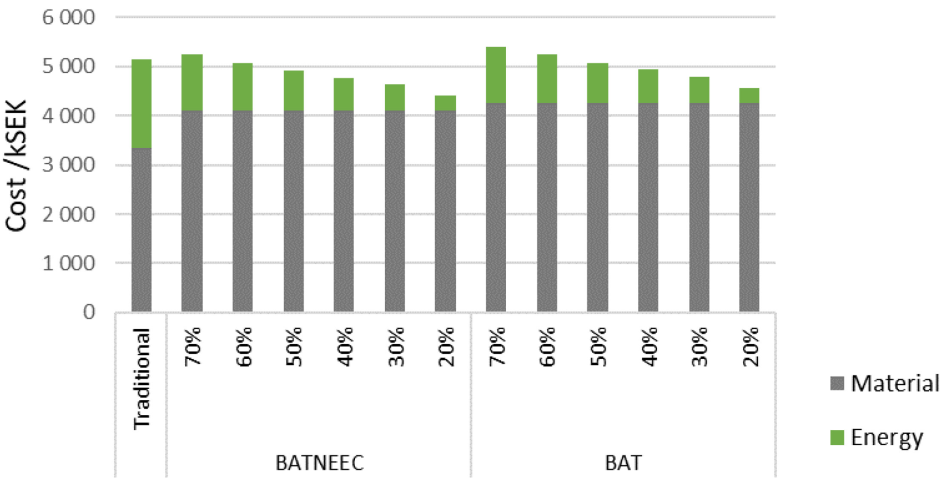


Figure 27.The NPV for material and operational energy use.

Payback time for these cases excluding the traditional base case was calculated in years, see Table 34. Cases including the BATNEEC alternative show a shorter payback time due to the lower investment cost of installed materials in comparison to the BAT alternative.

Table 34. Payback time is calculated in years for different cases based on different average occupancy.

Case	**DCV : 70%**	**DCV : 60%**	**DCV : 50%**	**DCV : 40%**	**DCV : 30%**	**DCV : 20%**
BATNEEC	-	46	35	30	25	21
BAT	-	-	46	38	33	27

5.5.1 Sensitivity analysis – Energy Price

A sensitivity analysis with varying prices for electricity and district heating but a constant nominal interest rate of 4%, and nominal price change of 2.2%, was conducted. Figure 28, shows the effect the price variation has on the total NPV of all cases including all DCV operational cases between 70% to 20%. The calculation period is 50 years and the total NPV value is represented as a positive and negative value indicating a profitable and non-profitable investment respectively. NPV energy is the cost for the operational energy use but is shown as a positive value for a more comprehensive representation of the data.

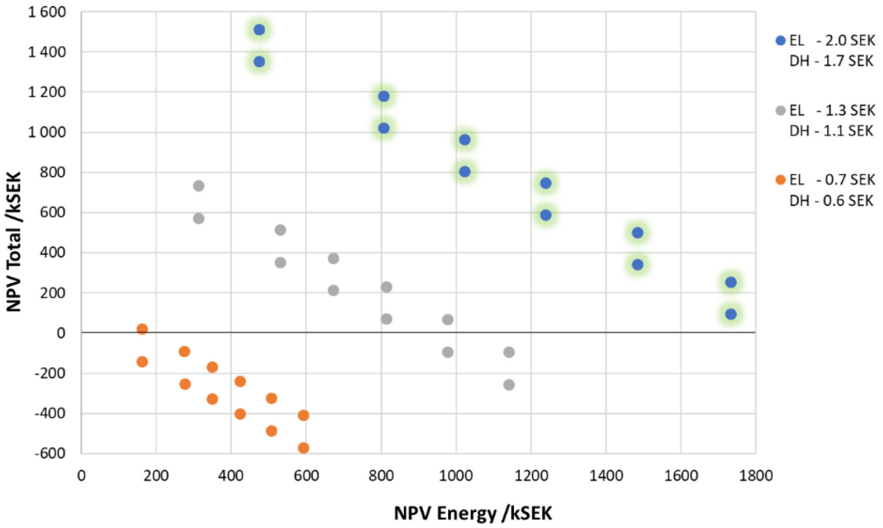


Figure 28. Sensitive analysis with energy prices 50% higher and lower than the current value.

The figure shows that there is an increase in the number of cases that become profitable due to the price increase, thus generating more savings and resulting in all cases becoming non-profitable with the price decrease. The best profitable cases that have a positive total NPV excluding the cases that apply to current energy prices, are highlighted in green in Figure 28 and are represented with a calculated payback time in Table 35, below.

Table 35. Payback time for best-performing cases excluding the cases with current energy prices.

EL = 2 SEK DH =1.7 SEK						
Case	**DCV : 70%**	**DCV : 60%**	**DCV : 50%**	**DCV : 40%**	**DCV : 30%**	**DCV : 20%**
BATNEEC	34	25	21	18	15	13
BAT	44	32	26	22	19	16

5.5.2 Sensitivity analysis – Interest rate

A sensitivity analysis with varying nominal interest rates but a constant nominal price change of 2.2%, and energy prices of 1.3 and 1.1 SEK for electricity and district heating was conducted. Figure 29, shows the impact of nominal interest rate variation on the total NPV of all DCV operational cases between 70% to 20%.

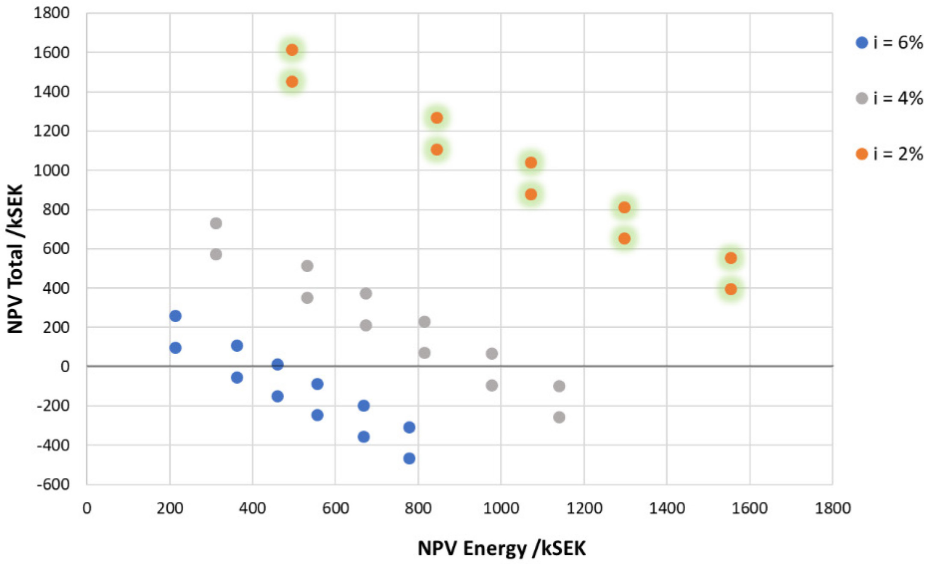


Figure 29. Sensitive analysis with an interest rate 50% higher and lower than the current value.

Figure 29, indicates an increase in the number of cases that become profitable due to the lower nominal interest rates and a decrease in the case numbers that are profitable due to the higher nominal interest rate. The best cases that have a positive total NPV excluding the cases that apply to an interest rate of 4%, highlighted in green, are represented with a calculated payback time in Table 36, below.

Table 36. Payback time for best-performing cases excluding the cases with the current interest rate.

i = 2%						
Case	**DCV : 70%**	**DCV : 60%**	**DCV : 50%**	**DCV : 40%**	**DCV : 30%**	**DCV : 20%**
BATNEEC	38	30	26	23	20	17
BAT	45	37	31	27	24	21

5.6 ILCA

The overall performance of the investigated cases including the traditional approach as well as the other cases created by combining the BATNEEC and BAT approach with the different operational alternatives was determined by an ILCA analysis. The results of the analysis assuming different economic and environmental weights ranging between 25%, 50%, and 75% are shown in Figure 30. The resulting performance value was internally normalized to the maximum for a better data representation and the case with the best performance was ringed in, see detailed calculation in Appendix F.

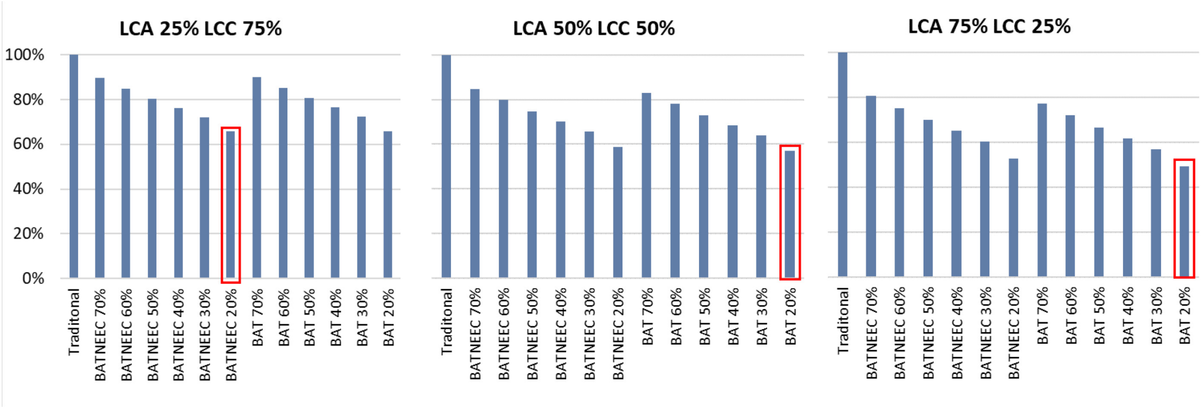


Figure 30. ILCA performance with different weighting factors for LCA and LCC.

When the weight for the LCA is greater than that for the LCC the case that performs best was BAT with an average operational schedule of 20%. This is because the BAT alternative incorporates both a DCV system and recycled steel, outperforming BATNEEC, which only includes the DCV system. This suggests that the environmental benefits associated with using recycled steel outweigh the additional costs incurred. The results also indicate that the lower the operational energy use is the better the case performs with a greater weight on the environmental impact.

By having an equal weighting factor for both LCA and LCC, the BAT alternative with 20% occupancy remains the top performer. However, when the weight for the LCC is greater than that for the LCC, the case with the BATNEEC alternative combined with an average operational schedule of 20% is the best-performing case. This indicates that cost considerations play a more significant role in decision-making when compared to environmental impact. Despite BATNEEC lacking the environmental benefits of recycled steel, its lower initial investment cost makes it a more profitable option. Moreover, the analysis indicates that decreasing operational energy use leads to a decrease in the total cost, eventually resulting in better performance.

5.7 Compilation

Table 37 below is a compilation of the results from the LCA and LCC calculation applied for the climate staircase followed by LFM30. For simplicity, the BATNEEC and BAT approach include the DCV system operating based on an average occupancy level of 50%. Main design strategies for the ventilation system are also summarised. The base level is included but was not provided with results regarding the environmental impact and cost due to the limitation of the study.

Table 37. LFM30 climate staircase including the approaches investigated.

	Traditional	**Base Level**	**BATNEEC (50%)**	**BAT (50%)**
$GWP_{A1\text{-}A5}$ /(kg CO_2e /m^2_{GFA})	23.1	-	22.7	18.3
$GWP_{B2,\ B4,\ B6}$ /(kg CO_2e /m^2_{GFA})	67.0	-	37.0	37.0
NPV Material /SEK	3 340 000	3 340 000	4 100 000	4 260 000
NPV Energy /SEK	1 810 000	-	820 000	820 000
Operation type	CAV	CAV	DCV	DCV
AHU	Designed for 100% occupancy level.	Designed for 100% occupancy level.	Designed based on actual occupancy level (80%).	Designed based on actual occupancy level (80%).
Duct system	Designed for 100% occupancy level.	Designed for 100% occupancy level. Compact layout.	Resized based on actual occupancy level (80%).	Resized based on actual occupancy level (80%). Use of recycled steel.
Flow dampers	Limited number of traditional flow dampers.	Limited number of traditional flow dampers. /Alternative Components.	Additional smart flow dampers.	Additional smart flow dampers.
Air terminals	Traditional air terminals.	Traditional air terminals. /Alternative components.	Active air terminals.	Active air terminals.

6 Discussion & Conclusion

The objective of this report was to investigate possibilities for optimizing the balance between life cycle stages A and B. Previous research indicated an imbalance by placing greater weight on either the production and construction stage or the operational usage stage. The study shows that focus can be placed on both stages to reduce the overall environmental impact. The results also showed that some measures in stage A do not have a direct impact on stage B such as the use of recycled material. Other energy-efficient measures might have the opposite by not affecting stage A but having significant effects on stage B such as the implementation of a DCV system.

Based on the results the subcomponents with the largest percentage of the total environmental impact in stages A1-A5 of a ventilation system are the AHU and the duct system including ducts and fittings combined. With the ducts being the second largest contributor and because they have a lower cost for installed material, the focus should be on the size reduction of the AHU which accounts for a very large mass of material more specifically steel, and having a higher cost with a need for reinvestment and maintenance. Special traits for this preschool include having a separate ventilation system for the kitchen area resulting in an overall impact for system LA02 characterized by a high amount of kg CO_2e per m^2 GFA but in reality, a moderate amount in kg CO_2e. This suggests that emissions are concentrated over a much smaller area, intensifying the emissions per unit area. Contributing to this is the airflow load provided by system LA02 mainly consisting of an AHU and a very small duct system to fulfil the requirement for forced airflow at maximum volume for five hours of the operation hours considering the moisture production and contaminated air in the kitchen area.

The LCA results across all cases were heavily influenced by the use of recycled steel which played a significant role in reducing the environmental impact from stage A for both systems LA01 and LA02 but had no effects on stage B. It is worth considering that these cases had a higher investment cost. Transitioning from a CAV system to a DCV system resulted in a negligible change and reduction in the emissions from stages A1-A5 for system LA01. This unchanged emission was caused by the fact that the duct system and AHU size reduction were evened out by the addition of active air terminals and smart flow dampers. On the other hand, the implementation of a DCV system although not impacting the production and construction stage, had a significant positive impact on the operational stage of the system. The operational energy use calculated with the occupancy level based on the interview resulted in a total of 20% higher emission in stage B6 compared to the operational energy use calculated with the occupancy level based on measured values. It is worth mentioning that uncertainties are present in both the occupancy schedule created based on the interviews and the measurements. Based on the interview a constant schedule was assumed over the period of a year which might not be accurate considering the fact that seasons and weather conditions can control the presence of children indoors and attendance also fluctuates over the year. The measurements were taken over a period of three days and were then generalized over the year which might imply a simplification and some uncertainties considering the fluctuations that might occur in the CO_2 levels during a larger period.

A parameter analysis was conducted to assess the impact of varying emission factor values for district heating and electricity based on several methods. Various locations were also considered affecting the operational energy use for district heating indicating that the higher the latitude the higher the energy use and the environmental impact. Results from the parametric study revealed that EPD yielded the lowest environmental impact, while Swedenergy had the highest when combining electricity and district heating. The extremely high values caused by the use of emission factors by Swedenergy are caused by the exclusion of renewable energy sources which shows the importance of sources and production methods of energy for the overall environmental sustainability. The variations in results indicate the importance of presenting unified and clear guidelines and methods that would ensure accurate results for stage B6.

The environmental impact GWP for installed materials for the traditional case, for both systems after 50 years does not fall below that for the operational stage. For LA01 it was 165% more and for LA02 it was higher by 7%. For the BATNEEC approach, GWP was still higher for the operational phase than that for the installed material even with a reduction in energy use of up to 50% by the implementation of a DCV system operating at an average of 50% of the occupancy level. In regards to the BAT approach, the emissions due to the production and construction stage are lower than the operation stage for both systems, irrespective of whether the operational average percentage based on the interviews or measured values was used. This deviation could be attributed to the significantly lower emissions in stages A1-A5 associated with the implementation of recycled steel.

fThe LCC revealed that the DCV system operating with a 20% occupancy schedule proves to be the most profitable by generating the most savings compared to the base case. The payback time for BATNEEC compared to BAT depends on the occupancy level, with lower occupancy resulting in more savings and a shorter payback time, typically ranging from 8 to 10 years or lower. However, BAT comes with a higher installation cost, particularly with the use of recycled steel. Implementing a DCV system alone reduces the operational energy use costs but comes with higher installation costs. It has been also shown that a DCV system operating with a percentage closer to 100% was not profitable considering the high investment cost.

In the pursuit of sustainable development, integrating both LCA and LCC through an integrated life cycle analysis offers a holistic approach to decision-making. By assigning greater weight to either LCA or LCC, the suitability of options can be determined. For average occupancies of 40% and 50%, the BAT alternative is the preferred choice when LCA carries more weight, while BATNEEC is the choice when LCC is prioritized. However, with equal weighting, BAT was found to be the most suitable choice. Despite longer payback times for BAT alternatives compared to BATNEEC, it is the best choice when constructing a ventilation system through an integrated life cycle assessment.

It is worth mentioning that there is potential in applying the climate stairs presented by LFM30 for renovation projects where similar steps can be followed in creating a climate deceleration for the base case and then implementing the measures investigated for a ventilation system in a preschool.

6.1 Further studies

It would be of great contribution to the field of the study to investigate the Base-level approach presented by the climate staircase of LFM30 where additional costs should not apply. It is of great challenge to find measures that can reduce the environmental impact of a ventilation system without additional costs. Measures discussed in this study were investigating the potential of redesigning the layout of the system creating a more compact and smaller system eliminating a number of components. The option of using alternative components that have a lower environmental impact per piece for the same cost is also a measure that can be investigated. Suggested components are silencers and air terminals which might require a detailed acoustic analysis to not undermine the performance of the system. In addition, a further study including all stages of the life cycle of a ventilation system would be of great importance and contribution to this study. It would allow a better understanding of what stage C and potentially D account for.

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Appendix

Appendix A: Operational energy for the traditional base case

The total operational energy use for LA01:

$$E_{HR} = 1.2 \cdot 1000 \cdot 4.605 \cdot (1 - 0.816) \cdot \frac{1960}{8760} \cdot 85\,600 = 19\,474\ kWh/year$$

$$E_{F(supply)} = \frac{472 \cdot 4.605}{0.7} \cdot 3640 = 11\,286\ kW/year$$

$$E_{F(exhaust)} = \frac{478 \cdot 4.605}{0.7} \cdot 3640 = 11\,446\ kW/year$$

$$E_{tot} = 19\,474 + 11\,286 + 11\,446 = 42\,206\ kW/year$$

The total operational energy use for LA02:

For the operational hours with the minimum airflow:

$$E_{HR} = 1.2 \cdot 1000 \cdot 0.2 \cdot (1 - 0.841) \cdot \frac{1160}{8760} \cdot 85\,600 = 433\ kWh/year$$

$$E_{F(supply)} = \frac{340 \cdot 0.2}{0.64} \cdot 2340 = 248\ kW/year$$

$$E_{F(exhaust)} = \frac{304 \cdot 0.205}{0.64} \cdot 2340 = 229\ kW/year$$

For the operational hours with the maximum airflow:

$$E_{HR} = 1.2 \cdot 1000 \cdot 0.67 \cdot (1 - 0.841) \cdot \frac{800}{8760} \cdot 85\,600 = 1000\ kWh/year$$

$$E_{F(supply)} = \frac{409 \cdot 0.67}{0.64} \cdot 1300 = 556\ kW/year$$

$$E_{F(exhaust)} = \frac{386 \cdot 0.685}{0.64} \cdot 1300 = 539\ kW/year$$

$$E_{tot} = (389 + 248 + 229) + (899 + 556 + 539) = 2\,954\ \ kWh/year$$

Appendix B: Operational energy for BATNECC based on interview

Corresponding pressure drop to its ventilation schedule.

Actual airflow/ Designed maximum airflow	Pressure drop - supply ; exhaust/ Pa
80 %	368 ; 375
65 %	325 ; 324
40 %	295 ; 302
33 %	290 ; 297
20 %	282 ; 290

80% $E_{HR} = 1.2 \cdot 1000 \cdot 3.684 \cdot (1 - 0.81) \cdot \frac{672}{8760} \cdot 85\,600 = 5\,510\ kWh/year$

$$E_{F(supply)} = \frac{368 \cdot 3.684}{0.66} \cdot 1248 = 2\,564\ kW/year$$

$$E_{F(exhaust)} = \frac{375 \cdot 3.684}{0.66} \cdot 1248 = 2\,613\ kW/year$$

$$E_{tot} = 5\,510 + 2\,564 + 2\,613 = 10\,687\ kW/year$$

Energy use for occupancy based on 65% to 20% is calculated the same way as for 80%, thus it is not presented.

Appendix C: Operational energy BATNECC based on measurement

Ventilation schedule and its corresponding pressure drop

Actual airflow/ Designed maximum airflow	Pressure drop – supply ; exhaust/ Pa
65 %	325 ; 324
50 %	306 ; 310
40 %	295 ; 302
33 %	290 ; 297
20 %	282 ; 290

65% $E_{HR} = 1.2 \cdot 1000 \cdot 2.993 \cdot (1 - 0.81) \cdot \frac{448}{8760} \cdot 85\,600 = 2\,987\ kWh/year$

$$E_{F(supply)} = \frac{325 \cdot 2.993}{0.66} \cdot 832 = 1\,226\ kW/year$$

$$E_{F(exhaust)} = \frac{324 \cdot 2.993}{0.66} \cdot 832 = 1\,222\ kW/year$$

$$E_{tot} = 2\,987 + 1\,226 + 1\,222 = 5\,435\ kW/year$$

Energy use for occupancy based on 55% to 20% is calculated the same way as for 60%, thus it is not presented.

Appendix D: Energy use calculation based on average occupancy level

Average value – 50%

$$E_{HR} = 1.2 \cdot 1000 \cdot 2.303 \cdot (1 - \ 0.81) \cdot \frac{1960}{8760} \cdot 85\ 600 = 10\ 057\ kWh/year$$

$$E_{F(supply)} = \frac{306 \cdot 2.303}{0.66} \cdot 3640 = 3\ 887\ kW/year$$

$$E_{F(exhaust)} = \frac{310 \cdot 2.303}{0.66} \cdot 3640 = 3\ 743\ kW/year$$

$$E_{tot} = 10\ 057 + 3\ 887 + 3\ 743 = 17\ 687\ kW/year$$

Average value – 40%

$$E_{HR} = 1.2 \cdot 1000 \cdot 1.842 \cdot (1 - \ 0.81) \cdot \frac{1960}{8760} \cdot 85\ 600 = 8\ 044\ kWh/year$$

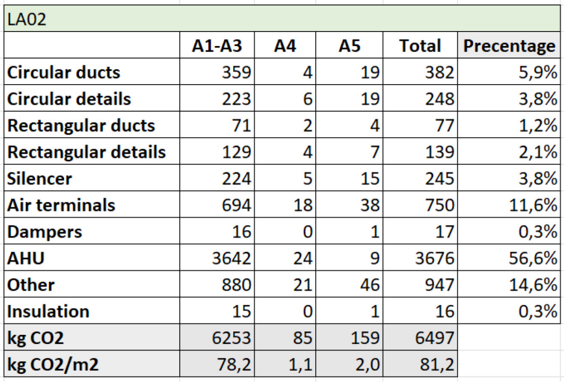
$$E_{F(supply)} = \frac{295 \cdot 1.842}{0.66} \cdot 3640 = 2\ 997\ kW/year$$

$$E_{F(exhaust)} = \frac{302 \cdot 1.842}{0.66} \cdot 3640 = 3\ 068\ kW/year$$

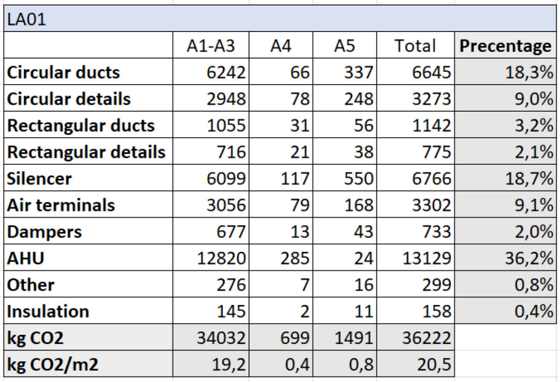
$$E_{tot} = 8\ 044 + 2\ 997 + 3\ 068 = 14\ 109\ kW/year$$

Appendix E. LCA calculation

Traditional

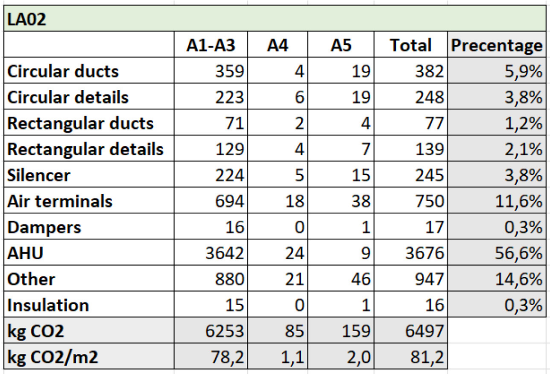


LA02					
	A1-A3	A4	A5	Total	Precentage
Circular ducts	359	4	19	382	5,9%
Circular details	223	6	19	248	3,8%
Rectangular ducts	71	2	4	77	1,2%
Rectangular details	129	4	7	139	2,1%
Silencer	224	5	15	245	3,8%
Air terminals	694	18	38	750	11,6%
Dampers	16	0	1	17	0,3%
AHU	3642	24	9	3676	56,6%
Other	880	21	46	947	14,6%
Insulation	15	0	1	16	0,3%
kg CO2	6253	85	159	6497	
kg CO2/m2	78,2	1,1	2,0	81,2	

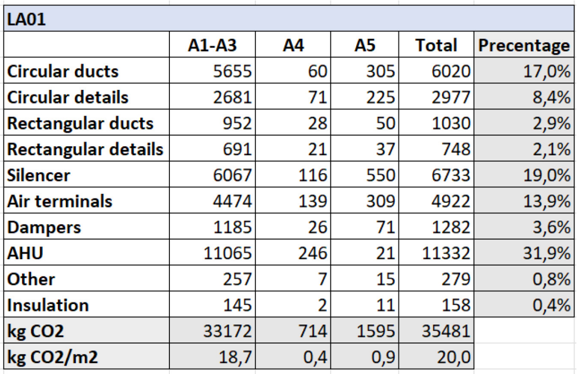


LA01					
	A1-A3	A4	A5	Total	Precentage
Circular ducts	6242	66	337	6645	18,3%
Circular details	2948	78	248	3273	9,0%
Rectangular ducts	1055	31	56	1142	3,2%
Rectangular details	716	21	38	775	2,1%
Silencer	6099	117	550	6766	18,7%
Air terminals	3056	79	168	3302	9,1%
Dampers	677	13	43	733	2,0%
AHU	12820	285	24	13129	36,2%
Other	276	7	16	299	0,8%
Insulation	145	2	11	158	0,4%
kg CO2	34032	699	1491	36222	
kg CO2/m2	19,2	0,4	0,8	20,5	

BATNEEC

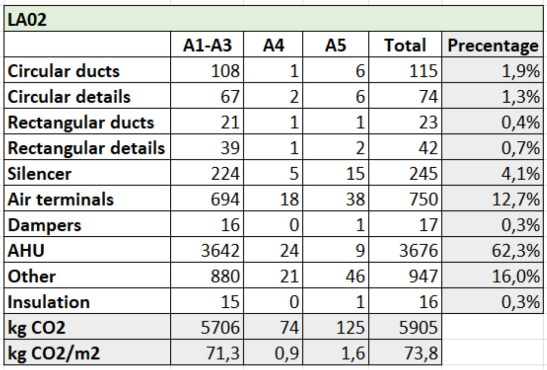


LA02					
	A1-A3	A4	A5	Total	Precentage
Circular ducts	359	4	19	382	5,9%
Circular details	223	6	19	248	3,8%
Rectangular ducts	71	2	4	77	1,2%
Rectangular details	129	4	7	139	2,1%
Silencer	224	5	15	245	3,8%
Air terminals	694	18	38	750	11,6%
Dampers	16	0	1	17	0,3%
AHU	3642	24	9	3676	56,6%
Other	880	21	46	947	14,6%
Insulation	15	0	1	16	0,3%
kg CO2	6253	85	159	6497	
kg CO2/m2	78,2	1,1	2,0	81,2	

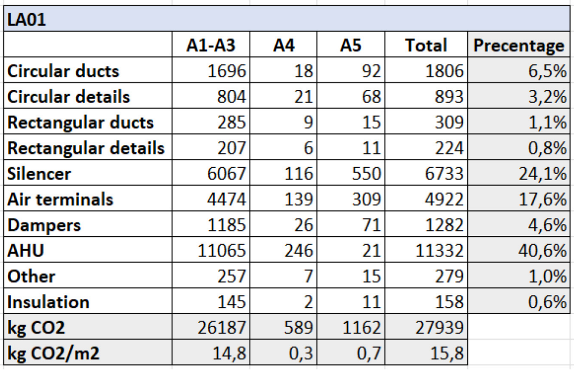


LA01					
	A1-A3	A4	A5	Total	Precentage
Circular ducts	5655	60	305	6020	17,0%
Circular details	2681	71	225	2977	8,4%
Rectangular ducts	952	28	50	1030	2,9%
Rectangular details	691	21	37	748	2,1%
Silencer	6067	116	550	6733	19,0%
Air terminals	4474	139	309	4922	13,9%
Dampers	1185	26	71	1282	3,6%
AHU	11065	246	21	11332	31,9%
Other	257	7	15	279	0,8%
Insulation	145	2	11	158	0,4%
kg CO2	33172	714	1595	35481	
kg CO2/m2	18,7	0,4	0,9	20,0	

BAT

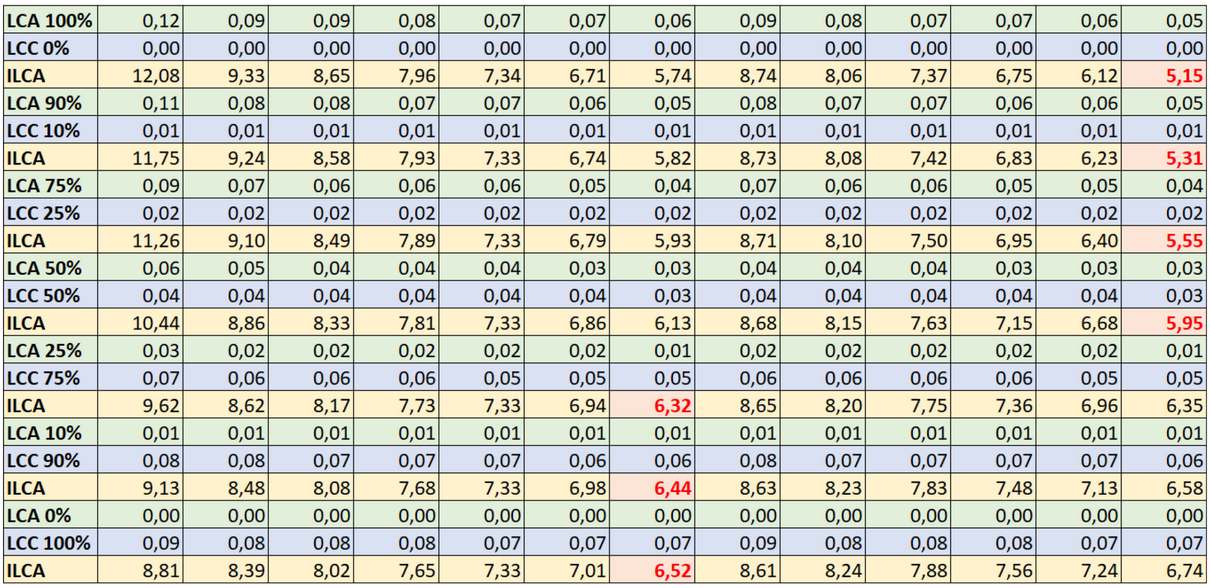


LA02					
	A1-A3	A4	A5	Total	Precentage
Circular ducts	108	1	6	115	1,9%
Circular details	67	2	6	74	1,3%
Rectangular ducts	21	1	1	23	0,4%
Rectangular details	39	1	2	42	0,7%
Silencer	224	5	15	245	4,1%
Air terminals	694	18	38	750	12,7%
Dampers	16	0	1	17	0,3%
AHU	3642	24	9	3676	62,3%
Other	880	21	46	947	16,0%
Insulation	15	0	1	16	0,3%
kg CO2	5706	74	125	5905	
kg CO2/m2	71,3	0,9	1,6	73,8	



LA01					
	A1-A3	A4	A5	Total	Precentage
Circular ducts	1696	18	92	1806	6,5%
Circular details	804	21	68	893	3,2%
Rectangular ducts	285	9	15	309	1,1%
Rectangular details	207	6	11	224	0,8%
Silencer	6067	116	550	6733	24,1%
Air terminals	4474	139	309	4922	17,6%
Dampers	1185	26	71	1282	4,6%
AHU	11065	246	21	11332	40,6%
Other	257	7	15	279	1,0%
Insulation	145	2	11	158	0,6%
kg CO2	26187	589	1162	27939	
kg CO2/m2	14,8	0,3	0,7	15,8	

Appendix F. ILCA scores



LCA 100%	0,12	0,09	0,09	0,08	0,07	0,07	0,06	0,09	0,08	0,07	0,07	0,06	0,05
LCC 0%	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
ILCA	12,08	9,33	8,65	7,96	7,34	6,71	5,74	8,74	8,06	7,37	6,75	6,12	**5,15**
LCA 90%	0,11	0,08	0,08	0,07	0,07	0,06	0,05	0,08	0,07	0,07	0,06	0,06	0,05
LCC 10%	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01
ILCA	11,75	9,24	8,58	7,93	7,33	6,74	5,82	8,73	8,08	7,42	6,83	6,23	**5,31**
LCA 75%	0,09	0,07	0,06	0,06	0,06	0,05	0,04	0,07	0,06	0,06	0,05	0,05	0,04
LCC 25%	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02
ILCA	11,26	9,10	8,49	7,89	7,33	6,79	5,93	8,71	8,10	7,50	6,95	6,40	**5,55**
LCA 50%	0,06	0,05	0,04	0,04	0,04	0,03	0,03	0,04	0,04	0,04	0,03	0,03	0,03
LCC 50%	0,04	0,04	0,04	0,04	0,04	0,04	0,03	0,04	0,04	0,04	0,04	0,04	0,03
ILCA	10,44	8,86	8,33	7,81	7,33	6,86	6,13	8,68	8,15	7,63	7,15	6,68	**5,95**
LCA 25%	0,03	0,02	0,02	0,02	0,02	0,02	0,01	0,02	0,02	0,02	0,02	0,02	0,01
LCC 75%	0,07	0,06	0,06	0,06	0,05	0,05	0,05	0,06	0,06	0,06	0,06	0,05	0,05
ILCA	9,62	8,62	8,17	7,73	7,33	6,94	**6,32**	8,65	8,20	7,75	7,36	6,96	6,35
LCA 10%	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01
LCC 90%	0,08	0,08	0,07	0,07	0,07	0,06	0,06	0,08	0,07	0,07	0,07	0,07	0,06
ILCA	9,13	8,48	8,08	7,68	7,33	6,98	**6,44**	8,63	8,23	7,83	7,48	7,13	6,58
LCA 0%	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
LCC 100%	0,09	0,08	0,08	0,08	0,07	0,07	0,07	0,09	0,08	0,08	0,08	0,07	0,07
ILCA	8,81	8,39	8,02	7,65	7,33	7,01	**6,52**	8,61	8,24	7,88	7,56	7,24	6,74

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

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

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

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

5) I used GAI for translations --> NO

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

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