MC2023
Proceedings of 12th Masters Conference: People and Buildings
University of Westminster, 15th September 2023
Network for Comfort & Energy Use in Buildings: https://www.nceub.org.uk

Low Embodied Carbon Ventilation Systems for Healthy Learning Spaces: comparative analysis of systems to provide fresh air in temperate climates.

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Abstract: While carbon neutrality is targeted for 2050, the building sector is responsible for significant GHG emissions but has a mitigation potential of 66% according to the IPCC. Public projects are given particular attention. However, MEP systems still account for 13% of the embodied carbon emissions in schools, and little effort is shown to reduce them. While passive cooling is well studied, much less is known about passive strategies to supply fresh air. This research provides a comparative analysis of passive, hybrid and active systems designed to provide fresh air to classrooms in temperate climates. Five case studies with heat recovery and CO_2 sensors are investigated through interviews and site visits. The paper outlines recommendations to prioritise passive strategies whilst maintaining adequate levels of IAQ. A life-cycle embodied carbon assessment of three system types found that the selected hybrid system leads to a reduction in the carbon emissions associated with HVAC.
Keywords: embodied carbon, ventilation, classroom, passive, hybrid

1. Introduction and Methodology

In line with the Paris Agreement, achieving carbon neutrality by 2050 is key to mitigating the effects of climate change (UNTC, 2015). Lack of environmental data on Mechanical, Electrical and Plumbing systems (MEP) suggests that the associated embodied carbon emissions have been underestimated so far. Heating, Ventilation, and Air Conditioning systems (HVAC) are often made of carbon-intensive metals with components of short lifespan. Their whole life cycle should be considered in carbon assessments.

Passive strategies, such as wind-driven and stack-effect ventilation, are a good way to use ambient energy and limit the number and size of systems. However, concerns about Indoor Air Quality (IAQ) raised by the Covid-19 pandemic and heat loss during winter have discouraged the use of passive strategies in schools. As a result, active systems are chosen.

While natural ventilation for passive cooling has been extensively studied, less is known about their potential to provide fresh air in high occupancy classrooms. This research proposes a comparative analysis of passive, hybrid and active ventilation systems to provide fresh air in temperate climate schools, with CO_2 sensors and heat recovery.

The research aims to outline a set of recommendations that can be used by designers to encourage the implementation of passive strategies and to motivate the reduction of carbon emissions associated with HVAC. Three objectives are set: to investigate the potential of passive and hybrid ventilation systems in meeting indoor air quality targets in temperate climates; to identify the characteristics of passive and hybrid ventilation systems and their implementation in the design process; to assess the embodied carbon emissions associated with passive and hybrid systems in comparison to a mechanical system.

The first section provides the theoretical background; the second section discusses the result of the fieldwork with five case studies; the last section presents the assessment of the life cycle embodied carbon emissions of three ventilation systems.

2. Background

2.1 The Importance of Life Cycle Embodied Carbon Assessment

The consensus on climate change is clear, and reducing emissions from human activities is crucial (IPCC, 2023). Several Greenhouse Gases (GHGs) absorb and release infrared radiation emitted by the Earth with varying intensity and duration. Carbon dioxide (CO_2), one of the main GHGs, is the baseline with a Global Warming Potential (GWP) of 1 (Bradshaw, 2006).

The building sector is a significant contributor, emitting 39% of the global GHG emissions (WGBC, 2023). The industry has made efforts to reduce Operational Carbon Energy emissions (OCE) in recent decade and is now focusing on Life Cycle Embodied Carbon emissions (LCEC) (RICS et al., 2023; LETI, 2020) but this shift has yet to be officially regulated (Part Z, 2021).

BS EN 15978:2011 set the standards for assessing the environmental performance of the whole life cycle of buildings (BSI, 2011). Based on Environmental Product Declarations (EPDs) that gives the GWP (kg CO_2e) of building elements, assessments of MEP are underestimated by lack of data, while their components are composed of carbon-intensive metals [Fig.1]. The TM65 basic calculation method is used to assess components with no evidence (CIBSE, 2021).

Figure 1. MEP components in a school construction site, Mermoz School, Rosny-Sous-Bois, FR (Site visit, 2023)

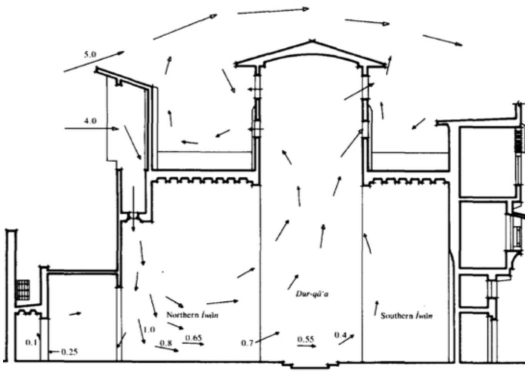

Figure 2. Section in a traditional windcatcher (Fathy, 1986) found in (Ford et al., 2020)

2.2 The large range of Ventilation Systems

Air management is closely related to the building's relationship between the indoor and outdoor environments. Wind-driven and buoyancy-driven passive systems remind us of the opportunities offered by fundamental principles. Used in vernacular architecture for centuries, they provide fresh air and cooling [Fig. 2] (Ford, Schiano-Phan and Vallejo, 2020).

Active systems allow conditioning of the indoor environment, “excluding” the outdoor constraints (Hawkes, 2022). Their use should be limited to specific situations as they consume generated energy to operate (Banham, 1969). School projects often rely on passive systems only for cooling during summer, in parallel to mechanical ventilation. Heat recovery units in natural ventilation systems makes it possible to limit heat loss in the exhaust air (Bradshaw, 2006) and creates opportunities for an efficient hybrid system to be used all year round.

2.3 Controls of Air Quality and Quantity

Ventilation is not only a matter of quantity, to provide enough fresh air for the occupants, but also of quality, to ensure that the fresh air provided is free from pollutants (BREEAM, 2018).

While outside air pollution is one of the major environmental risks to health (WMO, 2023), efforts continue towards a healthier indoor environment in educational buildings. Building Management Systems (BMS) regulate a demand-controlled ventilation based on a maximum CO_2 concentration, ensuring satisfactory levels of IAQ (Building Bulletin, 2018).

3. Fieldwork: Cases studies

3.1 Key Learnings from Interviews and Site visits

Below are the lessons learned from an extensive fieldwork study, which included the selection of five case studies, a series of semi-structured interviews with stakeholders and site visits.

Selected schools are located within 50km of London or Paris and fall in the Köppen Geiger climate zone Cfb (Temperate, No Dry Season, Warm Summer) but these classifications may evolve if the IPCC RCP 8.5 is followed (Beck et al., 2018). They are closed in summer, and the annual occupancy pattern is largely in the heating period, making the use of heat exchanger relevant [Fig.3] as there is a great difference between indoor and outdoor temperatures.

The sample illustrates the wide variety of systems between active and passive (Building Bulletin, 2018) and help to identify drivers and barriers to the design of passive strategies. Even more than mechanical ventilation, passive and hybrid systems must adapt to the constraints of microclimate, occupancy, acoustics, and air pollution [Fig.4].

Figure 3. Crossflow plate heat exchanger, Simone Veil School, Rosny-Sous-Bois, FR (Site visit, 2023)

Figure 4. Low air and acoustic pollution in front of Southwark PRU, London, UK (Site visit, 2023)

3.2 Selection of Three Ventilation Types

The passive system (T1) is made of a roof unit to catch the wind, a heat exchanger, two supply ducts to deliver fresh air at a low level and two return air diffusers in the ceiling. The hybrid system (T2) is made of a fresh air intake above the window, a heat exchanger, a glass wool supply duct, and a stack with a fan driven by the wind, or by electricity when needed. The active system (T3) is a classic balanced Air Handling Unit (AHU) with supply and return ducts.

A detailed review of these three ventilation types [Fig.5] shows that building services are evolving, driven by environmental certifications and collaborative work. User control is facilitated but the passive and hybrid systems seem to be derived from a mechanical design approach, not using full potential of passive principles. They are designed to meet IAQ targets (Lipinski et al., 2017; Switch, 2022) but their embodied carbon emissions are unknown.

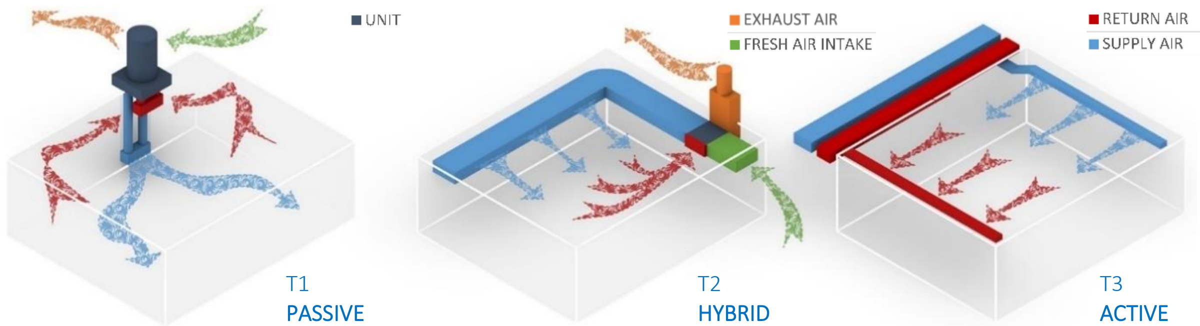

Figure 5. Axonometric view of three different types of ventilation systems installed in a classroom

4. Analytical work: Life Cycle Embodied Carbon assessment

4.1 Precedents and Methodology

Keyhani et al. (2023) estimated the embodied carbon of an educational building in the UK, but this analysis did not take into account MEP systems, nor did it look at the impact per floor area unit. Benchmarks such as the London Plan Guidance estimates the LCEC of schools at a value below 1,000 $kgCO_2e/m^2$ GIA, of which 15% is associated with MEP services (GLA, 2022).

An assessment of the LCEC emissions of three ventilation systems including modules A1-C4 and excluding B6-B7 is carried out over 60 years. The assessment covers at least 95% of the components based on EPDs and on the CIBSE TM65 basic calculation for the units.

A hypothetical school building is designed according to BB103 (Building Bulletin, 2014), with 16 classrooms of 30 people (8.6x7.2x3.0 m), arranged over two storeys of eight rooms with a central corridor. The sizing is based on a common airflow rate of 8 l/s/p (i.e., 240 l/s per classroom). 3D modelling of the three systems with the software Rhino made it possible to list and measure all components. Three lifespan scenarios are considered for the unit, as per interviews. Two new parameters are proposed in this study: the service risers' structural reinforcement (steel profile 31 kg/m), and the wasted floor area occupied by service risers and machine rooms (461 kg CO_2e/m^2). The results are normalised in kg CO_2e/m^2 GIA.

4.2 Limitations of the assessment

The study considers only three specific systems, and the results cannot be generalised as typical values for the system category. The main limitation is the availability and quality of data (e.g., EPD missing, unverified or incomplete, transport scenario). This study does not include operational energy, and therefore does not include refrigerants. Beyond fresh air, this would have required heating and cooling strategies to be considered with a thermal analysis throughout the year, which is outside the scope of the study.

4.3 Results overview

Overall, the hybrid system T2 had the lowest LCEC values in all scenarios, between 30% and 43% lower than the active system T3, while the passive system T1 was in second place in the conventional and optimistic scenarios. This study demonstrate that the lifetime of the unit considered in the assessment had a significant impact on the results over a 60-year period [Fig.6]. The assessment also reveals the variable impact of other components: the hybrid system T2 wasted 11 times less floor area than system T3, and used glass wool ducts that were half as carbon intensive as the galvanised steel ones in the active system T3 [Table 1].

Table 1: Life Cycle Embodied Carbon of system T1, T2 and T3 over 60 years ($kgCO_2e/m^2$ GIA)

Part	T1	T2	T3
DUCTS	5.72	28.40	30.72
UNITS	76.68	41.07	63.05
RISERS	4.58	5.63	0.95
WASTED AREA	6.09	1.29	14.65
TOTAL	**93.05**	**76.40**	**109.37**

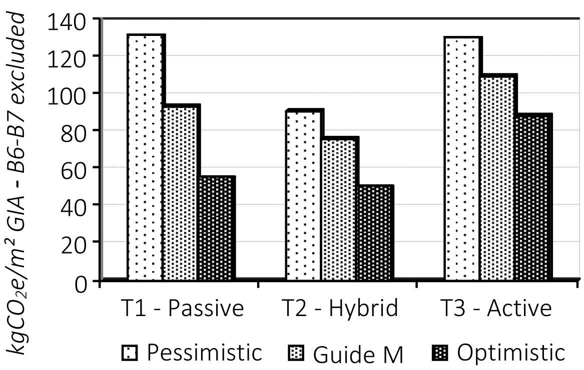

Figure 6. Life Cycle Embodied Carbon assessment of 3 unit's lifespan scenarios ($kgCO_2e/m^2$ GIA)

5. Discussion

Interpretation of the assessment should consider the additional OCE emissions. While T1 do not require generated energy (dampers neglected), T2 runs fans when passive strategies are not sufficient (SFP≈ 0.5 W/(l.s)) and T3 consumes electricity all-year (SFP≈ 1.5 W/(l.s)).

The passive system T1 is mainly wind-driven, but the localised fresh air supply may be heterogeneous and cause discomfort during winter. Its emissions depend on its lifespan. Ducts and chimneys could be integrated as building elements with high upfront carbon emissions that become effective over time. However, the impact of this vertical system would be amplified, further limiting layout evolution. Consideration of OCE emissions could highlight more benefits, as system T1 is also effective for passive cooling with a heat exchanger bypass.

In the hybrid system T2, the weak link is the roof fan, as it reduces by 75% the area of the exhaust duct and therefore, the potential for stack effect. Fans ensure IAQ continuity even on windless days, but are the moving components that are likely to determine the lifespan of the system if not maintained. A larger fan to facilitate natural ventilation or a photovoltaic panel for a self-generated system could be explored, but both solutions will increase the LCEC. Another solution to reduce the LCEC would be to combine fresh air and cooling strategies.

The system T3 offer a homogeneous airflow, but the AHU is only used for fresh air, as radiators are installed in the case study. Its combined use for heating, cooling and fresh air would increase its efficiency and reduce the carbon impact associated with HVAC, but would also require the use of carbon-intensive refrigerants and an increase in the dimension of the ducts. Other strategies could involve several lighter units made of more plastic than metal.

Overall, this research contributes to expanding the knowledge on ventilation systems in educational buildings. Although there is no simple solution, as many parameters need to be considered, the author recommends the following hierarchy. Firstly, natural ventilation should be facilitated in every project, with simple solutions that do not require generated energy and as early as possible in the design process. T1 is an interesting option for small classrooms if used on a long term, and CO_2 sensors are an effective way to monitor indoor air quality. Secondly, heat recovery and more advanced controls are implemented only when required by the climate and the occupancy. Indeed, they lead to air being ducted, which is not necessary with a passive strategy. The heat exchanger analysed is made of carbon-intensive aluminum, but significantly reduces the heating loads. Thirdly, mixed modes system, understood here as a combination of strategies rather than a multiplication of systems, are used when natural ventilation alone is not sufficient. T2 offers an interesting balance between embodied and operational carbon, but the mechanical component should not reduce the potential of passive strategies. Lastly, mechanical ventilation is used when specific requirements must be met, with appropriate sizing and a decentralised system where it is more efficient. T3 is indeed heavy in both operational energy and embodied carbon emissions, even if it provides a homogeneous and controlled air flow.

The applicability of this research is limited by its scope. It focuses only on ventilation to provide fresh air in temperate climates where heat recovery is appropriate. It also only considers general classrooms in new build, as other rooms or existing educational buildings may require different strategies. Moreover, this study only looked at the carbon emissions associated with the supply of fresh air in the systems used in the case studies.

This work is based on existing data. More information could be obtained from manufacturers. Schools are protected and difficult to visit. Continuous monitoring and post-occupancy evaluation would be an added value. Operational carbon, cost analysis, maintenance and circular economy should be explored in further research.

6. Conclusions

The paper outlined a set of recommendations to prioritise the use of passive strategies whilst maintaining adequate levels of IAQ. The LCEC assessment of three system types showed that the selected hybrid system leads to a reduction in carbon emissions associated with HVAC for fresh air in classrooms. The research has shown that ventilation is not only a matter of efficiency between quantity of air and energy, but also an essential component for space quality and occupant wellbeing. More needs to be done to reveal the accurate LCEC emissions associated with building services, to provide the essential missing information to decision-makers, to design better buildings and to mitigate the effects of climate change.

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8. Acknowledgements

Research part of the MSc AED at the University of Westminster, after a collaborative project with Hilson Moran. The author acknowledges the assistance of Dr. Rosa Schiano-Phan, Kartikeya Rajput, Dr Juan Vallejo, and all the participants: Switch, Rosny-Sous-Bois, Architecture Patrick Mauger, Waterman Group, David Morley Architects.