Should we ventilate differently in an adaptable context? An exploratory LCA-study

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Abstract. Currently a great number of buildings, that are not able to meet the evolving needs of building owners and users, are being demolished before reaching their technical life span. To avoid such waste, it is crucial that buildings have an adaptable design in order to allow for flexible building usage. Ventilation is crucial in this transition as a flexible building usage can lead to fluctuating ventilation requirements. However, knowledge about how to choose between ventilation systems in an adaptable context is sorely lacking. In this research, an exploratory LCA-study will be carried out on two ventilation systems in an adaptable context over a period of 15 years. The case study concerns a school building where a reconfiguration of the floorplan design is planned every five years. The first ventilation system concerns a centralized balanced mechanical ventilation system which uses a heat recovery system and ductwork to distribute the air to all the classrooms. The second ventilation system is a ductless exhaust ventilation system which uses three exhaust fans to extract air and vents above windows to supply air naturally. Despite the centralized balanced ventilation system having a higher energy efficiency, the environmental impact of this ventilation system is 40% higher than the impact of the ductless exhaust ventilation system. This is caused by the use of a great amount of ductwork and an air handling unit. The largest share of the environmental impact of the ductless exhaust ventilation system is related to the additional energy that is needed to condition the temperature in the classrooms. Further research should include other ventilation systems and flexibility scenarios as well. Moreover, follow-up research should not only quantify the environmental impact but also assess the financial impact of ventilation systems in an adaptable context.

Keywords. Adaptability, Circularity, Ventilation systems, Life cycle assessment
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1. Introduction

As buildings are becoming increasingly energy efficient, the share of material-related environmental impact has gained importance, both in absolute and relative terms [1]. To reduce this material-related environmental impact, the circular economy advocates using all materials and components to their maximum value [2]. However, a great part of our current building stock is being demolished long before its technical lifespan has been reached [3]. One of the main reasons that buildings are being dismantled prematurely, is that they cannot meet evolving needs from building owners and users. These evolving needs can vary [4–6]. To avoid this much building waste, buildings must be adaptable in order to allow for a more flexible usage.

The current state-of-the-art regarding adaptable buildings mainly stresses the importance of a smart spatial configuration [7–9] and the oversizing of building components to avoid future lock-in effects [10,11]. To ensure that an adequate indoor environment can be guaranteed over the entire life cycle of a building, ventilation systems should be considered in terms of adaptability as well. As a result, HVAC designers are facing a new challenge in designing ventilation solutions for an adaptable building practice. Instead of only considering the short term requirements, ventilation systems should be designed bearing the buildings entire life cycle in mind in order to ensure comfort, health, and energy efficiency under a wide range of possible future use scenarios.

As a flexible usage can lead to fluctuating ventilation requirements, ventilation systems are found to be a key factor with respect to the possibilities of adaptable buildings [12,13]. Changes in occupancy, floorplan layout and function of a room can result in a different normative air flow rate. Also in the long term a degree of adaptability is required, as the lifespan of ventilation systems is shorter than the lifespan of the entire building [14]. Therefore it is important that the components of ventilation systems can be easily replaced by new ones once their lifespan has been reached. Moreover, considering the long term, it is also important that ventilation systems do not hinder large refurbishments. Unfortunately, in many cases the ventilation systems have proven unsuitable to coping with an adaptable context [15,16].

This paper is innovative, as it is the first to quantify the environmental impact of two ventilation systems in an adaptable context. It concerns an exploratory case study of a school building where a reconfiguration of the floorplan layout is planned every five years. A life cycle assessment (LCA) will be carried out on two different ventilation strategies. The first one concerns a centralized balanced mechanical ventilation system. The second system is a ductless mechanical exhaust ventilation system with natural air supply through vents. The environmental impact of both ventilation systems will be compared over a period of 15 years.

2. Research Methods

In this research, an exploratory LCA-study will be carried out on two traditional ventilation strategies. A part of a school building will be used as a case study. Every five years the floorplan design will be reconfigured. The CO2 concentration in all classrooms will be simulated and the environmental impact of both ventilation systems will be assessed.

2.1 Case study

A part of a school building that is located in Belgium will be used as a case study. As this research focusses on adaptability, it is presumed that the floorplan design is reconfigured every five years. The original configuration contains six relatively small classrooms that are separated by demountable and reusable interior walls. In the second configuration four small classrooms are turned into two larger classrooms and in the final configuration there are only three large classrooms. The smaller classrooms are occupied by 20 persons and the larger classrooms by 30 persons. The three configurations are illustrated in Fig. 1.

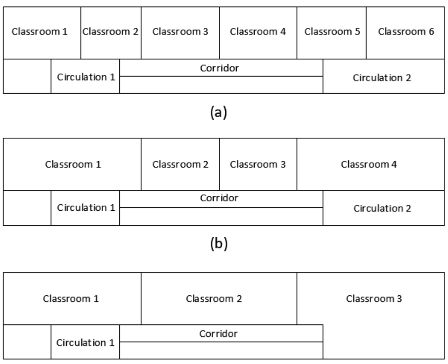

Fig. 1 - (a) Configuration 1; (b) Configuration 2; (c) Configuration 3

Two ventilation strategies will be compared to each other. The first one is a centralized balanced ventilation system with an inlet and outlet in all six classrooms. To ensure an adequate indoor air quality in classroom 3 for the third configuration, an additional inlet is provided in circulation room 2. This inlet will only be used when the last configuration is in use. The ductwork is designed so that the air velocity in the ducts is always between three and five meters per second. The central air handling unit is placed above classroom 3 and 4. This air handling unit does not include a heating or a cooling battery, but it does include a heat exchanger. The second strategy is a ductless mechanical exhaust ventilation system with natural air supply. There are three exhaust fans in use; one in each circulation room and one in the corridor. Fresh air will be naturally supplied through vents that are placed above a window in all six classrooms. The designs of both ventilation systems are illustrated in Fig. 2.

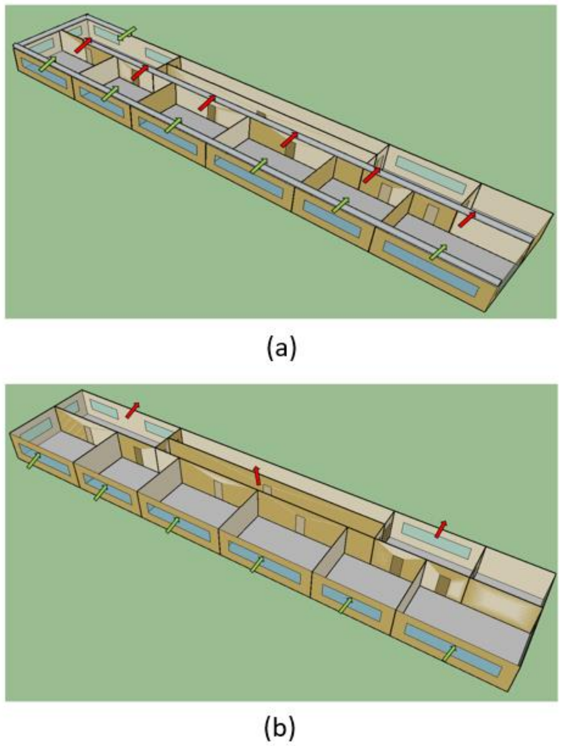

Fig. 2 - (a) Centralized balanced ventilation system ; (b) Ductless exhaust ventilation system

2.2 LCA

To quantify the environmental impact from both ventilation systems, an LCA-study will be carried out. As described in the framework provided by ISO 14040/44 [17], the following steps will be followed: Goal and scope definition, life cycle inventory (LCI) and life cycle impact assessment (LCIA).

Goal and scope. To create a level playing field, both ventilation systems are compared to each other with respect to the following functional unit: *a part of a school building where, during school hours over a period of 15 years, the maximum occurred* CO_2 *concentration is between 960 and 1000 ppm in all* *classrooms for every configuration and the temperature in the classrooms is at least 21 °C during school hours and 15.6 °C after school hours.* The entire life cycle of all the ventilation components are taken into account: the production-, the use- and the end-of-life-phase. In the case of ductless exhaust ventilation with natural air supply, the additional energy use that is needed for space heating, compared to the centralized balanced ventilation with heat recovery, is taken into account as well. Maintenance of the air handling unit and ductwork is not included in this study. Consequential LCA will be used over attributional LCA. Consequential LCA aims at describing how environmentally relevant flows will change in response to possible decisions [18]. Moreover, as this case study is situated in Belgium, the Belgian electricity mix will be used.

LCI. In Tab. 1 and Tab. 2 an overview is given of all the used materials and energy flows for both ventilation systems that are being included in this LCA-study. The air handling unit contains the fans and the heat recovery system. For the transport of materials to the site and the end-of-life-phase of materials, the scenarios provided by TOTEM [19] were used.

Tab. 1 - Life cycle inventory centralized balanced ventilation system.

Material	Unit
Air handling unit	Pieces
Ductwork	Meter
Wiring and control for centralized ventilation	Pieces
Energy consumption fans	kWh
Energy consumption heat exchanger	kWh

Tab. 2 - Life cycle inventory ductless exhaust ventilation.

Material	Unit
Exhaust fans	Pieces
Exhaust air outlet wall	Pieces
Exhaust air outlet roof	Pieces
Wiring and control for decentralized ventilation	Pieces
Energy consumption fans	kWh
Additional energy consumption for space heating	kWh

LCIA. To calculate the environmental impact of both ventilation systems, the Simapro software and the Ecoinvent database were used. The ReCiPe 2016 method is used and the environmental impact is presented as a single score.

2.3 Simulations

The software EnergyPlus (version 9.6) is used to carry out the energetic and indoor air quality simulations. An entire school year was simulated for every configuration for both ventilation strategies. Belgian holidays were included, except the months of July and August because school is closed during these months. The required energy needed for the fans and space heating for every configuration for both ventilation strategies was derived from these simulations and multiplied by five (as every configuration will be used for a period of five years). To calculate the required air flow rate from the fans to keep the CO_2 concentration between the range mentioned in the functional unit, the air flow network from EnergyPlus was used. The energy consumption by the fans was calculated manually. The energy consumed by the fans was calculated manually.

3. Results

In this section the results of the study will be discussed. First, the results derived from the simulations in EnergyPlus will be discussed. Hereafter, the results from the LCA-study will be discussed. All the precise calculations and the simulations can be found in the supplementary materials.

3.1 Space heating

The kind of ventilation system that is used will also have an impact on the amount of energy that is needed to condition the temperature in the classrooms. As stated in the functional unit, the heating system is scheduled to heat the classrooms up to 21 °C during school hours and up to 15,6 °C after school hours. A cooling system is not included in this case study. The results of the needed energy consumption for space heating are shown in Tab. 3. It can be deduced that the total energy that is needed to condition the temperature of the classrooms after 15 years, but also for every configuration, is less than half the amount in the case of the centralized balanced ventilation system compared to the case that uses a ductless exhaust ventilation system. This could be expected, since in the case of the ductless exhaust ventilation system, unconditioned cold air is taken into the classrooms through vents while the centralized balanced ventilation systems uses a heat recovery system. As a consequence, the heating system needs to deliver more energy to reach the required temperatures in the case of the ductless exhaust ventilation.

Tab. 3 - The energy needed to condition the temperature of the classroom for both ventilation systems.

	Centralized balanced VS [kWh]	Ductless exhaust VS [kWh]

Configuration 1	45429	93772
Configuration 2	37825	83781
Configuration 3	33602	69575
Total	116856	247128

3.2 Fans

Both ventilation systems should ensure an acceptable indoor air quality. As defined in the functional unit, the maximum CO_2 concentration that can occur in the classrooms is 1000 ppm. The maximum CO_2 concentration should also be above 950 ppm, in order to create a level playing field for both ventilation systems. In Tab. 4, the maximum CO_2 concentrations are shown for both ventilation systems and for every configuration that will occur in all six classrooms. From these results, it can be concluded that for every classroom the maximum concentrations are always within the predefined range.

Tab. 4 - Maximum CO_2 concentrations in all classrooms for both ventilation systems and all configurations.

	Centralized balanced VS [ppm]			**Ductless exhaust VS [ppm]**		
	Configuration 1	Configuration 2	Configuration 3	Configuration 1	Configuration 2	Configuration 3
Cl.1	985	967	972	991	984	979
Cl.2	986	959	974	991	999	970
Cl.3	985	968	972	972	999	994
Cl.4	986	973	*N/A*	972	980	*N/A*
Cl.5	990	*N/A*	*N/A*	999	*N/A*	*N/A*
Cl.6	990	*N/A*	*N/A*	999	*N/A*	*N/A*

Since the CO_2 concentrations meet the predefined requirements, the next step is to calculate the energy consumptions of the fans for both ventilation systems. As stated in the previous section, the energy consumption of the fans has been calculated manually. The results of the energy consumption from the fans can be found in Tab. 5. The energy consumption of the centralized balanced ventilation system contains the energy consumption from the supply and exhaust fan that are located in the air handling unit. The energy consumption of the ductless exhaust ventilation contains the energy consumption from the three exhaust fans that are located in the two circulation rooms and in the corridor. The results show that a much higher energy consumption is required in the case of centralized balanced ventilation. The reason for this is twofold. Firstly, in the case of the ductless exhaust ventilation system where the air supply happens naturally through the vent, a lower ventilation rate of the exhaust fans is required as natural forces such as wind also contribute to the ventilation of the classrooms. Secondly, the centralized balanced ventilation system has to cope with a lot more pressure losses because of the presence of extensive ductwork and other components such as a heat exchanger, which results in a higher energy consumption of the fans.

Tab. 5 - Energy consumption of the fans.

	Centralized balanced VS [kWh]	**Ductless exhaust VS [kWh]**
Configuration 1	16231	1309
Configuration 2	11584	574
Configuration 3	11486	281
Total	39302	2164

3.3 LCA

With the simulations and calculations of the energy consumption required for space heating and the use of the fans, everything is now in place to carry out the LCA-study. In **Error! Reference source not found.** and **Error! Reference source not found.**, an overview is given of the amount and the environmental impact of all the material- and energy related components in both ventilation systems. The environmental impact of all the used materials covers the impact of the production of these materials, the transport to the site as well as the end-of-life phase. The latter is accompanied with a negative impact since a large part of these materials will be recycled and thus partly avoids the production of new products.

When looking at the results from the centralized balanced ventilation system, it can be concluded that the ductwork has the largest environmental impact, followed by the air handling unit. These two components contribute up to more than 75% of the total environmental impact of the entire ventilation system. The energy consumption that is required for the fans and heat exchanger have the third and fourth largest environmental impact, respectively. The control and wiring have the smallest impact from the entire ventilation system.

Tab. 6 - Environmental impact centralized balanced ventilation system.

Material and energy usage	**Amount**	**Unit**	**Impact [Pt]**
Air handling unit	1	Pieces	460

Ductwork	114	Meter	765
Wiring and control	1	Pieces	14
Energy use fans	39302	kWh	329
Energy use heat exchanger	6278	kWh	53

The largest environmental impact of the ductless exhaust ventilation system is caused by the additional energy that is needed to condition the temperature in the classrooms. The environmental impact related to this energy consumption is responsible for more than 95% of the total environmental impact of this ventilation system. All the other components of this ventilation system and the energy consumption of the exhaust fans have an environmental impact that is relatively low. By contrast, the largest part of the environmental impact of the centralized balanced ventilation system was caused by the used materials and not by the energy consumption.

Tab. 7 - Environmental impact ductless exhaust ventilation system

Material and energy usage	Amount	Unit	Impact [Pt]
Exhaust fans	3	Pieces	3
Exhaust air outlet wall	2	Pieces	3
Exhaust air outlet roof	1	Pieces	4
Wiring and control	3	Pieces	20
Energy use fans	2164	kWh	18
Energy use space heating	130272	kWh	1090

In *Fig. 3*, the total environmental impact of both ventilation systems are compared to each other after a period of 15 years. From this graph it can be deduced that the environmental impact of the ductless exhaust ventilation system is approximately 30% lower than the impact of the centralized balanced ventilation system. Despite a great amount of additional energy being needed to condition the temperature of the classrooms in the case of the ductless exhaust ventilation system, the environmental impact of the great amount of ductwork and the air handling unit turns out to be higher still. However, once the school building is used more extensively, i.e. not only during school hours, the environmental impact related to the additional energy that is required to condition the temperature of the school building will increase. The environmental impact of the energy consumption by the fans in the centralized balanced ventilation system is also much higher than the energy consumption by the exhaust fans in the ductless exhaust ventilation system. The main reasons for this are the higher air flow rate and the pressure drops because of the ductwork and the use of a rotary wheel as a heat exchanger.

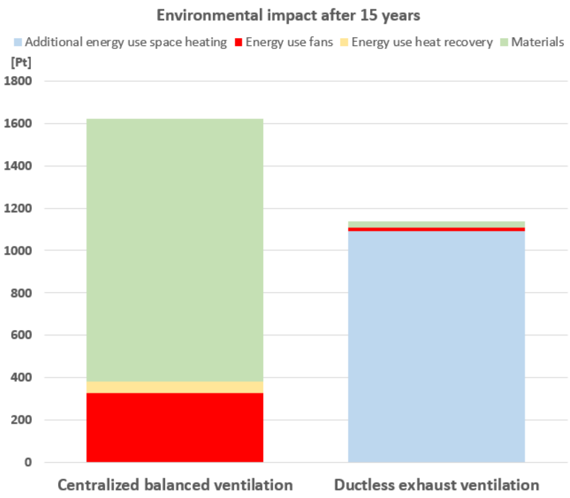

Fig. 3 - Comparison environmental impact.

4. Discussion

To obtain a better understanding on the meaning of this study, the results from this LCA-study will be analysed and discussed more thoroughly in this discussion section. Moreover, some recommendations for further research are formulated.

4.1 Discussion of results

The results from the LCA-study have shown that the environmental impact of the centralized balanced ventilation system is larger than the impact of the ductless exhaust ventilation system. The largest part of the environmental impact of the centralized balanced ventilation system is caused by the used materials, and not by the energy consumption of the fans. It is stated by Blengini and Di Carlo [20], that as buildings have become increasingly energy efficient, the share of material-related environmental impact has gained importance, both in absolute and relative terms. This also holds true for centralized balanced ventilation systems, based on the results from this LCA-study. While this ventilation systems is certainly more energy efficient than the ductless exhaust ventilation system, the environmental impact of the materials used for this ventilation system is much higher. In this specific case, the impact of the used materials is even so high, that the total environmental impact of this ventilation system is higher than the environmental impact of a ventilation system that is significantly less energy efficient. Yet a great number of studies focus mainly on the energy efficiency of ventilation systems, e.g.

Salcido et al. [21] and Jacobs and Knoll [22]. LCA-studies on ventilation systems, such as the study carried out by Fong et al. [23], are rather scarce.

However, it is important to stress that a ductless exhaust ventilation does not have a lower environmental impact than a centralized balanced ventilation system per definition. In this particular case, the building is only occupied during school hours. Once this school building is used in a more extensive way, the additional energy that is needed to condition the temperature of the classrooms will increase, and consequentially the environmental impact will as well. Therefore, it is possible that a ductless exhaust ventilation system has a higher environmental impact in a situation where the school building is being more frequently used. On the other hand, if a very energy efficient heating system is in use, the share of the environmental impact related to the additional energy needed to condition the temperature of the classrooms decreases.

Finally, it should also be stated that although some boundary conditions were imposed in this study, i.e. the maximum CO_2 concentration and the minimum temperature in the classrooms, the level of comfort both ventilation systems can guarantee is not completely equal. Parameters such as the relative humidity, draught and the maximum temperature were not included as this is only an exploratory case study which can form a basis for further research in the topic of ventilation in an adaptable context.

4.2 Further research

This is the first LCA-study carried out on two ventilation systems in an adaptable context. There are, however, many more ventilation systems that can allow for a flexible building usage. The environmental impact of these systems should be assessed as well. Moreover, there are also far more ways of using a building in a flexible manner than merely by altering the floorplan layout. For example, school buildings can be used after school hours as well. The activities that take place in school buildings can also fluctuate over time. It is important to understand how other kinds of flexible building usage influence the environmental impact of several ventilation systems.

Moreover, the records from ventilation components from the Ecoinvent database that were used in this LCA-study are rather outdated. Therefore it is important for follow-up research to use more accurate data about all the components used, i.e. the materials they consist of, where and how these components are made, the maintenance these components require and what happens with these components after their technical life span has been reached.

Finally, the authors also encourage carrying out a life cycle cost assessment (LCCA) on ventilation systems in an adaptable context, besides only an LCA-study. An example of such a study, is the study carried out by Buyle et al. [24] where both the environmental and financial impact of several internal walls were compared to each other over a period of 60 years with a reconfiguration of the floorplan design layout planned every 15 years. Based on both the environmental and financial consequences of a ventilation system, building owners can then make an informed decision on which system they prefer. Flexibility scenario's must be taken into consideration as a building is often used in a flexible way.

5. Conclusion

In this paper an exploratory LCA-study was carried out on two different ventilation systems in an adaptable context over a period of 15 years. A part of a school building where the configuration of the floorplan layout was changed every five years was used as a case study. The first ventilation system concerns a centralized balanced ventilation system which uses a heat recovery system and a great amount of ductwork to distribute the air. The other system was a ductless exhaust ventilation system. Air was supplied naturally through vents placed above windows in all classrooms and air was extracted through three exhaust fans. Despite the centralized balanced ventilation being more energy efficient, it has a higher environmental impact than the ductless exhaust ventilation system. This is caused by the environmental impact related to the great amount of ductwork and the air handling unit. The largest environmental impact of the ductless exhaust ventilation system is related to the additional energy that is required to condition the temperature of the classrooms. In this case study, the school building was only occupied during school hours. If the school building were to be used more extensively, the environmental impact of the ductless exhaust ventilation system would increase and might even be higher than the environmental impact of the centralized balanced ventilation system.

Further research should also include other ventilation systems and take into account other flexibility scenarios, e.g. a more extensive building usage and other types of building usage. Besides quantifying the environmental impact, the financial impact should be quantified as well by means of an LCCA-study. Based on these results, building owners can then make an informed decision on which ventilation system they prefer.

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The datasets generated during and/or analysed during the current study are available in the

Supplementary data.zip repository, [https://blackboard.uantwerpen.be/bbcswebdav/xid-32842002_1·](https://blackboard.uantwerpen.be/bbcswebdav/xid-32842002_1)

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