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Ventilation's role in adaptable school buildings: comparing traditional and adaptable strategies through life cycle assessment

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Abstract

Adaptable buildings are a promising enabler in the transition towards a more circular economy, with the ambition of using materials as efficiently as possible. To exploit adaptable buildings to their full potential, HVAC designers should critically rethink how to design technical services and ventilation systems in particular. This case study illustrates how five ventilation strategies perform from an environmental point of view in a school building where the configuration of the floorplan changes every five years, each of the changes reflecting a pedagogical vision. Consequential LCA is used to assess the environmental impact. A decentralized balanced mechanical ventilation system, which requires almost no adaptations when the configuration changes, has the lowest environmental impact while mechanical exhaust ventilation has the highest. However, when the configuration of the floorplan layout alters more rapidly, the relative environmental impact of the latter decreases substantially. The main conclusion is that, in a flexible context, the material-related environmental impact gains importance over the energy-related impact. With respect to this conclusion, a key finding is that minimizing the material use of ductwork (rather than oversizing ductwork dimensions to decrease the energy consumption of the fan) is more sustainable from an environmental point of view. Finally, distributing the ductwork over two shafts offers more flexibility and results in a lower environmental impact as this allows for the use of smaller dimensions of ductwork.

Keywords: Ventilation; Adaptable buildings; Life cycle assessment; Circular economy; School buildings

Word count: 9730

1. Introduction

Although ventilation is crucial for ensuring a healthy indoor environment, it is unclear how to optimally design ventilation systems for buildings which are intended to be used in a flexible manner. In particular, this is the case for school buildings with a potential for polyvalent usage after school hours, with a wide heterogeneity in user needs across the different stakeholders.

The building sector is in transition towards the circular economy [1], which aims to overcome the divergent interests of economic and environmental prosperity by closing material loops through technological innovation as well as by introducing new business models [2]. In this approach, more attention is paid to rational material use, which makes sense as buildings have become more energy efficient in recent years. The material-related environmental impact increased per building [3]. Moreover, to date construction materials are often used rather inefficiently as a great part of our current building stock ends up obsolete as their rigid design cannot facilitate the evolving needs of building users [4,5]. As a result, buildings are often demolished prematurely leading to high costs and substantial amounts of construction and demolishing waste. Integrating a certain degree of adaptability in the design of buildings can be a promising strategy to avoid this inefficient use of resources. Adaptable buildings yield the potential to evolve with the needs of building owners and users, thus extending the service life of buildings [6–8]. Moreover, buildings that allow for a flexible usage can in turn be used more extensively which increases its economic value [9].

A great body of research has been conducted in the field of adaptable buildings because of their substantial environmental and economic potential, see for example the work of Askar et al. [5] and Heidrich et al. [10] who summarized the current state-of-the-art concerning adaptable buildings. This has led to conceptual guidelines to increase the adaptability of buildings, such as an opting for smart spatial configuration [11–13] and an oversizing of structural building components to avoid future lock-in effects [8,14].

However, a flexible building usage can also imply fluctuating requirements from technical services. Seuntjens et al. [15] categorize flexible building usage into short- and long-term flexibility, both with distinct building requirements. The latter concerns large refurbishments which take place after several decennia. In this case, the adaptability of technical services is often neglected, given their short technical life span which is often estimated between 7 and 25 years [7,16,17]. It is therefore presumed that when a large refurbishment occurs, the technical services are already outdated and should be replaced. Nonetheless, flexible building usage can also occur in the short term. For example, a building can serve multiple functions within the timespan of a day. Technical services must be able to respond to these varying occupancy rates and activity levels. Also, in buildings that are intended to be used in a flexible way in the mid to long-term, there will be consequences that affect the requirements of technical services. For example, a building's floorplan may change after a few years to meet changing needs [18–20]. Flexible partitions or demountable and reusable walls can be used to achieve this. HVAC designers should take this into account since a new floorplan may impact the design of technical services. A new layout of spaces may, for example, result in the need to relocate the supply and exhaust ventilation terminals. Or a new floorplan layout can also lead to new occupancy rates in several zones which were not considered in the original design of technical services.

These types of short-term flexible usages of buildings are particularly relevant in the context of school buildings. With school-community partnerships becoming more common, schools share their infrastructure with the local community [21]. This requires infrastructure which allows for an intensive multifunctional usage. Secondly, new educational methods are often accompanied with changing infrastructural needs [22]. Demountable and removable walls can be a suitable solution to facilitate these changing needs. However, technical services must be reconciled with a short-term flexible building usage to ensure a healthy environment at all times. Therefore, it has been stated by Geraedts [12] and Kronenburg [23] that technical services are found to be a key factor with respect to using buildings in a flexible manner.

However, in many cases the technical services have proven to be unsuitable to cope with fluctuating requirements [14,24,25]. Out of all technical services, ventilation systems are the most difficult to match with a flexible building usage from a constructional point of view. Besides ensuring an adequate indoor air environment, they are also rather voluminous which can cause practical issues. An overview on the current literature to increase the adaptability of ventilation systems has been developed by Seuntjens et al. [15], where guidelines were categorized into five categories: accessibility, oversizing, distribution, controlling strategy and technical circularity.

Although these guidelines are important to understand how ventilation systems can reconcile with a flexible context, the final goal is to translate these guidelines into practice [26], and to design the most sustainable ventilation systems in the long run. HVAC systems can consume up to 40% of the total energy consumption in office buildings in the EU [27]. In the commercial sector in Hong Kong, ventilation alone can even account for 30% of the total electricity usage [28]. A method to critically assess and quantify the environmental impact, is a life cycle assessment (LCA). LCA is a method to analyze environmental burdens and benefits of a product, process or service, considering their whole life cycle, from cradle to grave [29]. Such a critical evaluation of the environmental impact is especially important in a flexible context since adaptable solutions are often oversized. This, in turn, leads to a greater impact related to the production and extraction of materials.

However, only few LCA studies are carried out on ventilation systems despite their substantial environmental impact. To assess which ventilation strategy is the most sustainable, Fong et al. [28] carried out an LCA on three ventilation methods, i.e. mixing, displacement and stratum ventilation, and compared their environmental impacts using a school as a case study. Stratum ventilation turned out to have the lowest environmental impact due to the lowest material and energy consumption. However, this study is caried out in a static context. To understand which strategies are the most sustainable in a flexible context, case studies are required in which flexible building usages are included. One exploratory case study researches the environmental impact of a centralized balanced mechanical ventilation system and a ductless mechanical exhaust ventilation system in a school building where the configuration of the floorplan changes over time [30]. Another example where a flexible building usage is considered is a study carried out by Buyle et al. [31] where the replacement of several types of walls, both conventional and reusable wall designs, are compared on the basis of a consequential LCA. It was found that when a high frequency of change is required, the demountable and reusable walls performed better in comparison with the conventional ones. On the other hand, when a limited amount of modifications are required over time, conventional walls had a lower environmental impact. Quite apart from the fact that ventilation has not been included in this research, it is also important to note that this study was conducted in isolation from any case specific context. When comparing several solutions in a flexible context, it is critical that the usage scenarios are effectively based on the needs of stakeholders in order to reach robust conclusions [32].

To sum up, to date it is unclear how to sustainably include ventilation in an adaptable building while accounting for the needs of stakeholders. To tackle this knowledge gap, this research aims at analyzing how ventilation can be reconciled with a school building that is used in a flexible manner from an environmental point of view. This general objective is achieved by answering the following research questions: (1) how do traditional and alternative ventilation strategies compare to each other in a flexible context, based on their environmental impact, (2) how do several design strategies influence the environmental impact and (3) how does the material-related compare to the energy-related environmental impact in a flexible context?

The innovativeness of this paper relates to how ventilation can be included in adaptable buildings while accounting for the needs of stakeholders and contributes to the growing domain of quantitative evaluation of circular strategies. To the author's knowledge, this is the first case study where the environmental impact of several ventilation strategies is compared in a flexible context by means of an LCA study. In addition, going beyond the often engineering-oriented scenarios in many LCAs, the flexible use scenarios are based on the needs of educational stakeholders, bridging technology oriented research with social sciences. The needs were identified in focus group discussions, which distinguishes this paper from other studies where flexible use scenarios are neglected or arbitrarily chosen.

2. Materials and methods

To answer the research questions, a case study is evaluated based on the floor plans of an existing school building in Belgium. The flexibility scenarios build on previous research where focus group discussions were organized in which educational stakeholders discussed how educational and societal needs would develop in the future and how school buildings should anticipate on these expected changes [33]. Based on the results of this study, a case is developed where four different configurations of the floorplan layout are selected, each of them reflecting a specific teaching method. The configuration changes every five years.

In this context, an LCA is carried out on five different ventilation strategies, ranging from traditional to more alternative ones, over a period of 20 years. To analyze the trade-off between materials and energy, the design of the ductwork is optimized in three different ways. Finally, to assess the robustness of the results, five sensitivity analyses are included.

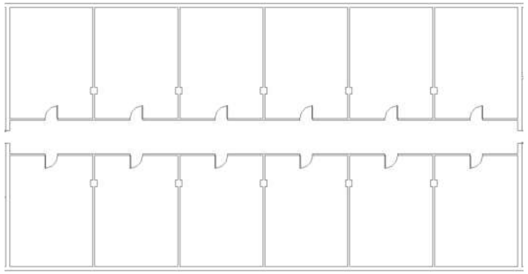
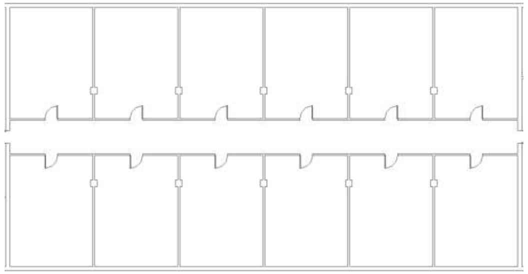
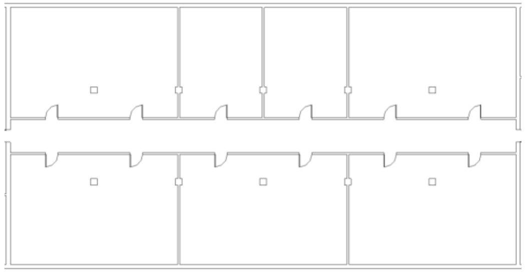
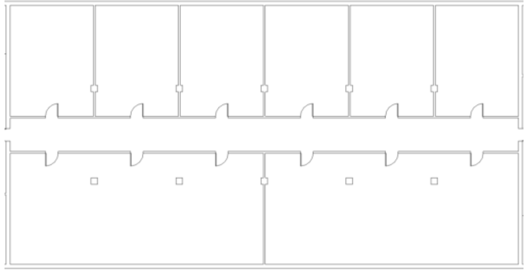
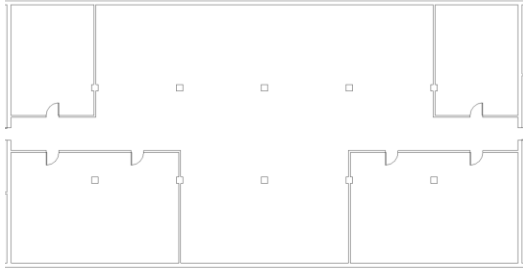
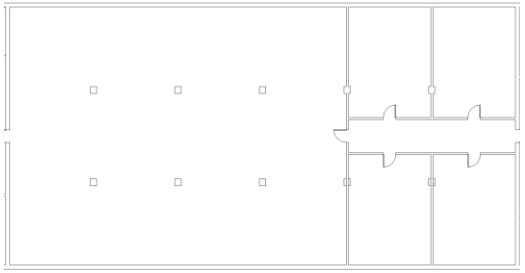
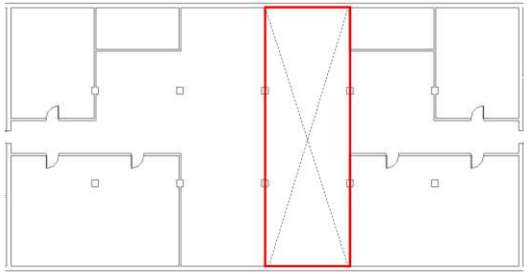
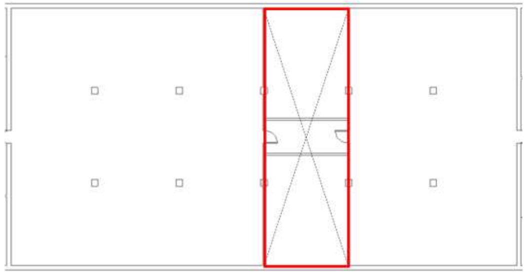
2.1. Case study

The selected case concerns a school building which is located in Mechelen (Belgium) and has the following properties:

- Net surface area of 1877 m², distributed over two equal floors
- The insulation level of the school building complies with the Flemish energy regulations of 2022 [34]
- A heat pump with an average COP of 2.5 is used to heat and cool the school building
- Heating setpoint: minimum 21°C during school hours and 15.6°C after school hours
- Cooling setpoint: maximum 26°C during school hours and 30°C after school hours

The flexible use scenario includes changing the configuration of the school's floor plan every five years. Four configurations are derived from earlier work by Seuntjens et al. [33], in which educational stakeholders discussed how educational needs would develop and how the infrastructure should evolve with these changing needs. An overview of the selected configurations and their characteristics is shown in Table 1. The first two configurations, where several classrooms are connected by a corridor, facilitate more traditional teaching methods. The difference between these two, is that in the second configuration some larger classrooms are formed by removing interior walls. The last two configurations, based on an open space plan, are characterized by multiple types and sizes of spaces with specific applications, e.g. a media room, a low-stimuli room, a multifunctional space etc. In the final configuration, an atrium interconnects the entire building. These type of configurations can be used for more modern teaching methods, like team teaching. More detailed information about the case can be found in the Supplementary material.

Table 1. Overview different configurations

Configuration	Level 1	Level 2	Characteristics
1			• Traditional floorplan • Small classrooms • 480 students
2			• Traditional floorplan • Smaller and larger classrooms • 480 students
3			• Open space plan • Wide variety of spaces and rooms • 320 students
4			• Open space plan • Wide variety of spaces and rooms • Atrium (marked in red) • 300 students

2.1.1. Ventilation scenarios

To ensure a healthy indoor environment for all building occupants, the Flemish regulations prescribe an air flow rate of 22 $m^3/(h*person)$ for every space that is intended for human occupation [34]. Compared to the AHSRAE standard [35], which prescribes a minimum required air flow rate of 17 $m^3/(h*person)$ in classrooms, the Flemish regulations are stricter. To meet this requirement, several ventilation strategies can be applied. In total, five different ventilation strategies are selected and implemented in this case study. An overview of all these strategies can be found in Table 2.

Three strategies are centralized balanced mechanical ventilation systems which are equipped with a rotary heat exchanger. While the first is the most commonly applied system in new schools, the other two are low-pressure systems, which are known for their lower fan energy consumption, i.e. diffuse ceiling ventilation and under floor air distribution [36,37]. The fourth strategy is a mechanical exhaust ventilation system where the air is supplied naturally through vents. The final strategy is a decentralized balanced mechanical ventilation systems where 24 smaller air handling units, equipped with a counterflow heat exchanger, are placed in the building.

Regarding the design of the ductwork, i.e. the trace and the dimensions, a design optimization method developed by Kabbara et al. [38], which elaborates on the work from Jorens et al. [39], is applied. This method optimizes the design of the ductwork based on a variety of cost optimization objectives, including material costs, fan energy costs or the life cycle cost which includes both material and energy costs. Considering these objectives, three different scenarios are selected to optimize the design of the ductwork. The first scenario aims at minimizing the fan energy cost of the system by minimizing pressure drops throughout the ductwork system. By reducing pressure drops as much as possible, the system can operate more energy-efficiently, resulting in lower fan energy consumption. The second scenario focuses on using as few materials as possible in the design configuration to minimize the material costs. Contrary to the other scenarios, where multiple trace choices are considered, this scenario involves imposing a specific trace that requires minimal adaptations when the configuration of the floorplan changes. By constraining the design to a predetermined trace, the need for new ductwork is minimized. While the first two scenarios might be conflicting, the final scenario considers the trade-off between the ductwork material and fan energy usage by minimizing the life cycle cost. The design optimization attempts to achieve a balance between increasing energy efficiency and reducing material use by taking this trade-off into account. Herewith, the aimed design looks for an ideal solution that balances maximizing energy efficiency while minimizing material usage. While these three scenarios are included in the first ventilation strategy, only the third scenario is included for the other ventilation strategies. Finally, it is important to stress that despite the design optimization objectives, all the resulting design solutions adhere to design feasibility constraints, i.e. maximum dimensions of the ductwork and air velocities.

Finally, it must be stipulated that not every ventilation strategy can facilitate each configuration. First, the diffuse ceiling ventilation system can only be used for configuration 1 and 2 since the corridor can be used for the extraction. However, when switching towards configuration 3 and 4, there is no corridor anymore and the entire space should be ventilated. This means that a lowered ceiling should be placed over the entire level, which leaves no space to extract the air in a decent manner. Second, there is an important boundary condition in configuration 4. In this configuration, a part of the floor slab of the second floor is removed, creating an atrium which is highlighted in red in Table 1. As a constraint, no ductwork is allowed in this area. To deal with this constraint, two shafts, positioned at opposite ends of the school building, and two air handling units are required. Therefore, each ventilation strategy is divided into two scenarios where first uses one shaft while the second uses two shafts to distribute the ductwork over the building.

Table 2. Overview selected scenarios and their properties. Legend: x = applicable; Blank = not applicable; LC = Lowered Ceiling; RF = Raised Floor

Ventilation strategy	Scenario name	**Design choices**							**Applicable for configuration**			
		Design ductwork			Number of shafts		Additional measures		1	2	3	4
		Energetically optimized	Material minimization	Combination	1	2	LC	RF				
1. Centralized balanced mechanical ventilation	Cen_mv[L1_S1]	x			x				x	x	x	
	Cen_mv[L1_S2]	x				x			x	x	x	x
	Cen_mv[L2_S1]		x		x				x	x	x	
	Cen_mv[L2_S2]		x			x			x	x	x	x
	Cen_mv[L3_S1]			x	x				x	x	x	
	Cen_mv[L3_S2]			x		x			x	x	x	x
2. Diffuse ceiling ventilation	Dcv[L3_S1]			x	x		x		x	x		
	Dcv[L3_S2]			x		x	x		x	x		
3. Under floor air distribution	Ufad[L3_S1]			x	x			x	x	x	x	
	Ufad[L3_S2]			x		x		x	x	x	x	x
4. Mechanical exhaust ventilation	Mev[L3_S1]			x	x				x	x	x	
	Mev[L3_S2]			x		x			x	x	x	x
5. Decentralized balanced mechanical ventilation	Dec_mv								x	x	x	x

To include ventilation strategies which cannot facilitate all four configurations, three building usage scenarios are included and analyzed. They entail different consecutive orders in which the configuration of the floorplan changes. The time gap between each switch is still five years for each building usage scenario:

- Building usage scenario 1: Con. 1 → Con. 2 → Con. 3 → Con. 4
- Building usage scenario 2: Con. 1 → Con. 2 → Con. 3 → Con. 1
- Building usage scenario 3: Con. 1 → Con. 2 → Con. 1 → Con. 2

2.2. Life cycle assessment

To assess the environmental impact of all the discussed ventilation strategies, an LCA is carried out based on the ISO 14040 and 14044 standards [29,40]. The three steps described in the standard are outlined here.

2.2.1. Goal & scope definition

A consequential LCA (CLCA) is carried out following the theoretical framework of Weidema et al. [41] to compare and assess the environmental impact of different ventilation strategies. CLCA aims to describe how environmentally relevant flows will change in response to possible decisions [42]. Within this methodological framework, all ventilation strategies are compared with respect to the following functional unit (FU):

"*The hygienic ventilation of a school building, for which the properties are described in 2.1, for a period of 20 years during school hours where the configuration of the floorplan layout changes every five years and includes the following set of configurations: {X}.*"

Where X corresponds to the three predefined building usage scenarios, described in section 2.1.1, resulting in respectively FU 1, FU 2 and FU 3. It is important to note that an under floor air distribution system differs from other ventilation strategies since the raised floor is placed directly on the floor slab while this is not the case for other ventilation strategies where a screed and ceramic tiles are also a part of the floor construction. Therefore, an additional FU is included where the additional non-structural floor layers are taken into account as well for ventilation strategies other than the under floor air distribution. This FU is called FU 1' since it follows the same building usage scenario as FU 1. The choice of a 20-year time frame is based on the average life span of technical services [17].

Aesthetic functional requirements, such as a lowered ceiling or visible air handling units in classrooms, are not taken into account as these are highly user dependent.

2.2.2. Inventory analysis

The life cycle inventory is based on how flows and activities are affected by a change in demand for a product or a process. Therefore, it is important to identify the marginal suppliers, i.e. the activities that are affected by a change in demand. The four steps described in the framework from Weidema et al. [41] are followed to determine the marginal suppliers. In the first step, the time horizon is determined. This study focusses on the long term and presumes small changes, and it is therefore assumed that markets are fully elastic. The second step, where the geographical market boundaries are delimitated, is one of the most important ones. The two most key materials are steel and aluminum. Based on reports from the sector federations Worldsteel Association [43] and International Aluminium [44], it can be concluded that both materials are global commodities. As a default in this CLCA, other, less frequently used materials are treated as global commodities unless the existence of dominant local markets can be justified [45]. For example, energy consumption during the use phase and waste treatment are modelled as local processes, at a national level for Belgium [46]. The third step entails examining market trends. Trade and production data from sector federations clearly show that steel and aluminum are growing markets, meaning that the competitive suppliers are the most likely to respond to a change in market demand [43,44]. Finally, the suppliers which are most sensitive to a change in demand must be identified. For this task, marginal suppliers are selected that are included in the consequential database from Ecoinvent. It is important to note that constrained suppliers can never respond to a change in demand, e.g. by-products follow the market trends of the determining (main) product or secondary raw material use is supply instead of demand driven. So as a consequence, input materials are assumed to be primary ones and the environmental benefits of recycling are quantified as a recycling potential, i.e. reclaimed products replace their primary (and marginal) counterparts at some point in the future.

With respect to this consequential framework, the required data for the ventilation systems is collected. Existing records from the Ecoinvent v3.9 database were used. However, these records are manually adjusted based on information from technical datasheets to obtain more accurate and up to date results. Moreover, for the technical life span of all components, the report from CIBSE [47] is used. The transport and end-of-life phase of the used materials are based on the data from a Belgian governmental report on the environmental profile on building components [46]. Regarding the replacement losses that occur when the configuration changes, it is assumed that 5% of the ductwork, diffusers, lowered ceiling and raised floor cannot be reused and are assumed to be treated according to the current practice in Belgium. All other components can be fully reused. Maintenance is excluded since this merely includes dry cleaning of components, which has a neglectable environmental impact.

2.2.3. Impact assessment

To calculate the environmental impact, the software Brightway2 and Activity Browser is used. Two approaches can be used to quantify environmental impacts, i.e. problem-oriented (midpoints) and damage-oriented (endpoints) impact assessment methods [48]. The results from the latter tend to be less transparent and more subjective [49]. Therefore, the former approach is selected to quantify the environmental impact which is in line with the EN 15804 standard [50]. To present the results in a concise manner, one midpoint category is selected to express the environmental impact, i.e. global warming potential (GWP) from the hierarchist ReCiPe 2016 v1.03 method. Results from other midpoint categories show similar trends compared to GWP and are included in the Supplementary material.

2.3. Energy simulations

The energy-related environmental impact which is taken into account consists of two components. The first is the energy use of the ventilation system itself, i.e. the auxiliary energy of the fans and the energy used by the rotary heat exchanger. This is calculated manually, assuming a constant fan efficiency of 75% and a motor efficiency of 80% [51]. The pressure drops that occur in the ductwork are generated by the design algorithm. The pressure drops for the components, the filters, heat exchangers and diffusers, are retrieved from technical reports. The energy consumption of the rotary heat exchangers is calculated assuming they have a power of 180 and 90 Watt, for the larger and the smaller air handling unit respectively.

The second component is the energy use for space conditioning. This is related to the influence of the selected ventilation strategy on the heating and cooling demand of the building. Since this is an indirect effect of the choice of ventilation system, the LCA study includes the absolute difference in energy use between the ventilation strategies. The first three strategies, i.e. the centralized balanced mechanical ventilation system, the diffuse ceiling ventilation and under floor air distribution are all equipped with a rotary heat exchanger with an average efficiency of 80%. Consequently, they have the same energy demand for heating and cooling. The mechanical exhaust ventilation system is not equipped with a heat exchanger and thus will require more energy to heat and cool the building. Finally, the decentralized balanced mechanical ventilation system also has a different energy demand for heating and cooling. Although the heat exchangers in this system have the same average efficiency of 80%, they are not centralized like the first three, but distributed among the decentralized air handling units.

To calculate the energy demand for heating and cooling, dynamic simulations are performed using the Software EnergyPlus. All four configurations are implemented in this software and simulated separately. According to the Flemish standard, the U-value of the roof, floor and exterior wall cannot exceed 0.24 W/(m²*K) while the maximum U-value of the exterior windows is set at 1.1 W/(m²*K). The internal heat gains come from the students, each accounting for 100 Watts. The used climate model for the energy simulation is a weather file which is based on measured weather data in Antwerp (Belgium) between 2004 and 2018. The calculated total energy demand for heating and cooling is divided by the efficiency of the generating system, viz. a heat pump with an average COP for heating and cooling of 2,5. In the Supplementary material, a model of the energy simulation is included with more detailed information.

2.4. Sensitivity analysis

Several assumptions were made in this study. As the study covers a time span of 20 years, it cannot be ruled out that other pathways may occur. Therefore, sensitivity analyses (SA) are carried out to check the robustness of the results. In total, five sensitivity analyses are performed:

- SA 1: In the energy simulations, a weather file which represents the current climate is used. However, to determine whether global warming has an impact on the results, the energy simulations in EnergyPlus are carried out once more while using a weather file which represents a worst case futuristic climate. In concrete, a weather file is used which is developed by Ramon et al. [52]. The used climate model entails a typical downscaled year, based on the methodology of Nik [53], where the RCP 8.5 projection of the ICCP is applied on the period of 2070-2098 in Uccle (Belgium).
- SA 2.1: In the original study, it is assumed that the configuration of the floorplan layout alters every five years. Two additional scenarios are included where the configurations change more rapidly. In the first, it is assumed that the configuration changes every two and a half years. This means that the configuration changes seven times in total.

- SA 2.2: In the second additional scenario, it is assumed that the configuration of the floorplan changes each year. This means that the configuration changes nineteen times in total.
- SA 3: The environmental impact related to the energy consumption is based on the Belgian electricity mix, which in turn is derived from the EU reference scenario [54]. Based on the EU reference scenario, four different electricity mixes are developed which can be used for a period of five years, starting from 2020. In this sensitivity analysis, four alternative electricity mixes are used which are based on a more optimistic scenario, i.e. SSP2-NDC based on the REMIND framework [55]. This will reduce the energy-related environmental impact.
- SA 4: For the final sensitivity analysis, it is assumed that the replacement losses are 100% instead of 5%. This means that no materials are being reused when the configuration changes. Instead, all materials will enter their end-of-life phase which is described in [46]. The aim of this sensitivity analysis is to highlight the environmental gains that can be made by reusing materials as much as possible.

3. Results

In presenting the results, a distinction is made between the material- and energy-related environmental impact. The first subsection describes which components of the ventilation strategies cause the material-related environmental impact. Hereafter, the aggregated results are shown for all FUs and the sensitivity analysis. More detailed information can be found in the Supplementary material.

3.1. Impact materials

All selected ventilation strategies exist of several components. To identify which components have an environmental impact and to what extent, an overview is given in Figure 1 on the material-related environmental impact for configuration 1 for each ventilation strategy. Under floor air distribution is not taken into account, since this also affects the design of the floor.

The materials of the centralized balanced mechanical ventilation system and diffuse ceiling ventilation have the largest environmental impact. The only difference between both, is that the latter also uses a lowered ceiling, resulting in a 36% higher impact. The decentralized balanced mechanical ventilation and mechanical exhaust ventilation have the lowest impact, respectively 30% and 70% lower than the centralized balanced mechanical ventilation system. This is due to the fact that the former uses no ductwork and the latter no air handling unit and only half of the ductwork since the supply happens naturally.

When looking at the relation between the different types of components, it is found that the difference between the impact of the ductwork and the central air handling unit is relatively small. For the centralized balanced mechanical ventilation system, 60% of the total environmental impact is caused by the ductwork, while 40% is caused by the central air handling unit. Concerning the latter, 76% is caused by the components, mainly the heat exchanger and the fans, while 24% is caused by the casing. The opposite holds true for decentral air handling units, where the casing is responsible for 68% of the environmental impact while only 32% is caused by the components.

To summarize, the magnitude of the material-related environmental impact varies considerably per ventilation strategy. In addition, the difference in impact between the ductwork and the central air handling unit is limited for the initial configuration.

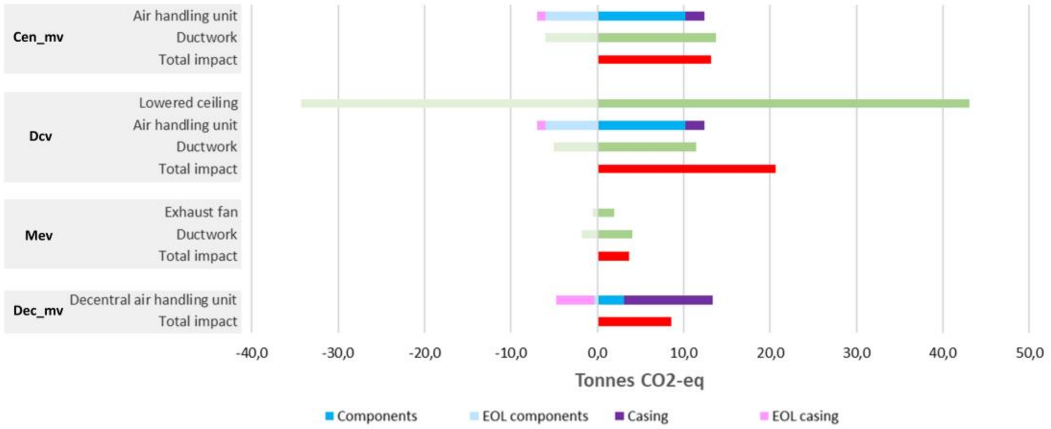


Figure 1. Environmental impact caused by materials used for configuration. EOL : End-of-life

3.2. Main scenarios

In Figure 2, the results of the LCA are shown for all FUs. Since some ventilation strategies are designed in multiple ways, as shown in Table 2, a range has been indicated for these strategies in which the environmental impact can occur.

This shows that for FU 1, decentralized balanced mechanical ventilation has the lowest environmental impact. The impact of the centralized balanced mechanical ventilation is higher within a range of 13 and 34%. The mechanical exhaust ventilation has the highest impact, emitting approximately 42 tonnes CO2-equivalent. The same pattern occurs for FU 2, although the best version of the mechanical exhaust ventilation can perform better than the worst version of the centralized mechanical ventilation system in contrast to FU 1. When looking at the results from FU 3, the best design version of the centralized mechanical system has a 3% lower environmental impact than the decentralized ventilation system. The mechanical exhaust ventilation has the highest impact while the diffuse ceiling ventilation has an impact which is 26 to 30% higher than the best version of the centralized mechanical ventilation. Finally, the decentralized ventilation has the lowest impact for FU 1’. Its impact is 9% lower than the environmental impact of the mechanical exhaust ventilation and the under floor air distribution. The best version of the centralized ventilation has an impact which is only 3% higher compared to the decentralized ventilation while the worst version also has a 9% higher environmental impact. The reason that emission of CO2-equivalents is up to three times as high compared to the other FUs, is that the floor layers, i.e. the screed and ceramic tiles, are taken into account as well for FU 1’ as discussed earlier.

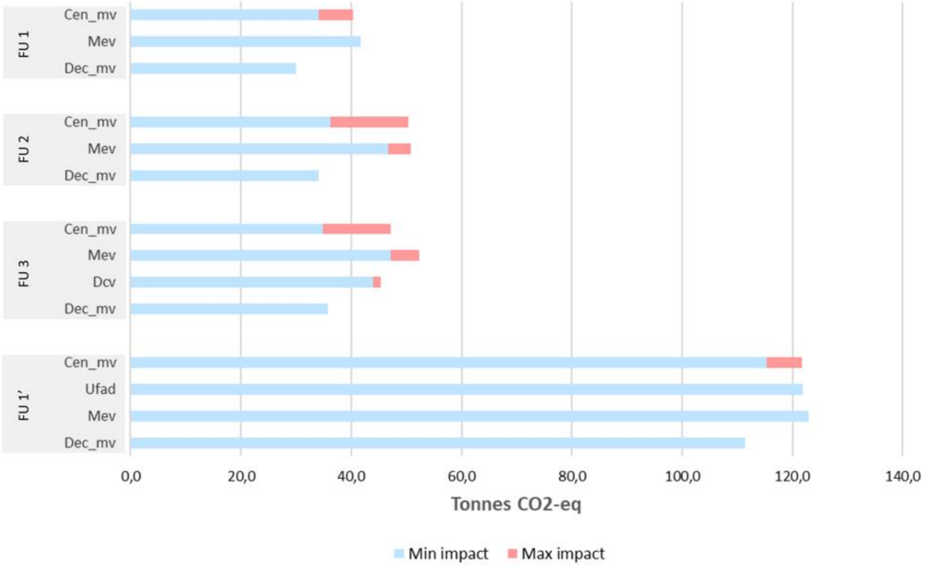


Figure 2. Environmental impact ventilation strategies for all functional units

In Figure 3, more detailed information is shown concerning the environmental impact of the different ventilation strategies. It turns out, from an environmental point of view, that there is a substantial difference regarding the design of the ductwork for the centralized balanced mechanical ventilation system. For all FUs, the energetically optimized design has the highest impact while minimizing the material usage of the ductwork results in the lowest environmental impact. For example, when looking at FU 1, the energetically optimized system has a 19% higher impact compared to the system minimizing its material usage. Despite the fact that the former consumes 8748 kWh less, it uses 5562 kg ductwork, almost twice as much as the latter. Only for FU 3, the combined optimization method results in the lowest environmental impact. For this FU, the necessary replacements are smaller as both configurations are very similar.

Secondly, it can be seen from the results that dividing the ductwork over two shafts has a smaller environmental impact, up to 12%, than using only one shaft. Although using one shaft requires fewer meters of ductwork, its total weight of ductwork is higher as it requires more voluminous ductwork compared to using two shafts where smaller ductwork can be used. Moreover, using two shafts also result in a slightly lower energy consumption of the fans as the total distance of the ductwork becomes shorter. This means that dividing ducts over two shafts has a double advantage. On the one hand, it has a smaller environmental impact and, on the other, it offers more freedom to use a building in a flexible manner.

Regarding the low-pressure systems, i.e. diffuse ceiling ventilation and under floor air distribution, their higher environmental impact is largely explained by the impact that is caused by the lowered ceiling and raised floor respectively as they use less ductwork compared to the centralized balanced mechanical ventilation.

The largest environmental impact is often caused by the mechanical exhaust ventilation. Notwithstanding the fact that it uses 1904 kg ductwork less than the centralized mechanical ventilation system, its energy-related impact is much higher. The energy that is required for heating and cooling emits more than 25 tonnes of CO2-equivalent than the energy that is required when using a centralized balanced mechanical ventilation system. It is however important to note that the energy level consumed by the fans is twice as low, as only one fan is required to exhaust the air mechanically. Still, this does not outweigh the indirect energy consumption related to the ventilation system.

Finally, the decentralized balanced mechanical ventilation system has the lowest environmental impact on the whole. From the results, it can be seen that this is mainly explained by the fact that almost no replacements of the ventilation systems are required when the configuration of the floorplan changes. In addition, it also has a relatively low initial environmental impact as shown in Figure 1.

3.3. Results sensitivity analysis

To assess the robustness of the results, a set of sensitivity analyses is carried out. All these sensitivity analysis are based on FU 1. The results can be found in Figure 4. In SA 1, the energy simulations are performed again while using a climate model which is based on the ECP 8.5 high end climate change scenario for Belgium for the period 2070-2098. It can be concluded that, although small changes occur in the energy consumption for heating and cooling, the main conclusions remain the same compared to when a climate model is used that represents the current climate situation.

In SA 2.1 and SA 2.2, the frequency with which the configuration of the floor plans changes is increased, respectively to two and a half and one year. This higher frequency implies a higher environmental impact for all ventilation strategies because more replacements are required. The only ventilation strategy where the environmental impact barely increases, respectively 5 and 17%, is the decentralized ventilation system since this strategy requires almost no replacements when the configuration changes. On the other hand, the impact of the centralized ventilation system can increase up to 37% when the configuration changes every 2,5 years or even up to 155% when it changes every year. With respect to the mechanical exhaust ventilation, the impact increases 14 and 65% respectively.

However, the magnitude of this increase depends on how the design of the ductwork is optimized. As the impact related to the replacements becomes greater, minimizing the material usage of the ductwork performs relatively better. Its environmental impact is 29% lower compared to a centralized ventilation system where the design of the ductwork is energetically optimized when the configuration changes every two and a half years and even 43% lower when the configuration changes every year.

Regarding SA 3, where a more optimistic electricity mix is used, is beneficial for ventilation strategies where a larger relative share from the total environmental impact is caused by energy consumption. This is mainly the case for the mechanical exhaust ventilation. Its total impact is almost halved by using this more optimistic energy mix making it the best ventilation strategy while it is the worst when the EU reference electricity mix is used. Moreover, the centralized ventilation system where the design of the ductwork is energetically optimized loses its energetical advantage and manifestly becomes the worst design optimization method from an environmental point of view.

SA 4 highlights the importance of a proper facility management to maximize the reuse potential and avoid unnecessary losses. For the centralized mechanical ventilation system this can lead to an environmental impact which is almost five times higher than in the scenario where all the ductwork is reused as much as possible. Regarding the mechanical exhaust ventilation, the total environmental impact more than doubles while the impact of the decentralized ventilation only increases with 17% as this strategy requires almost no replacements.

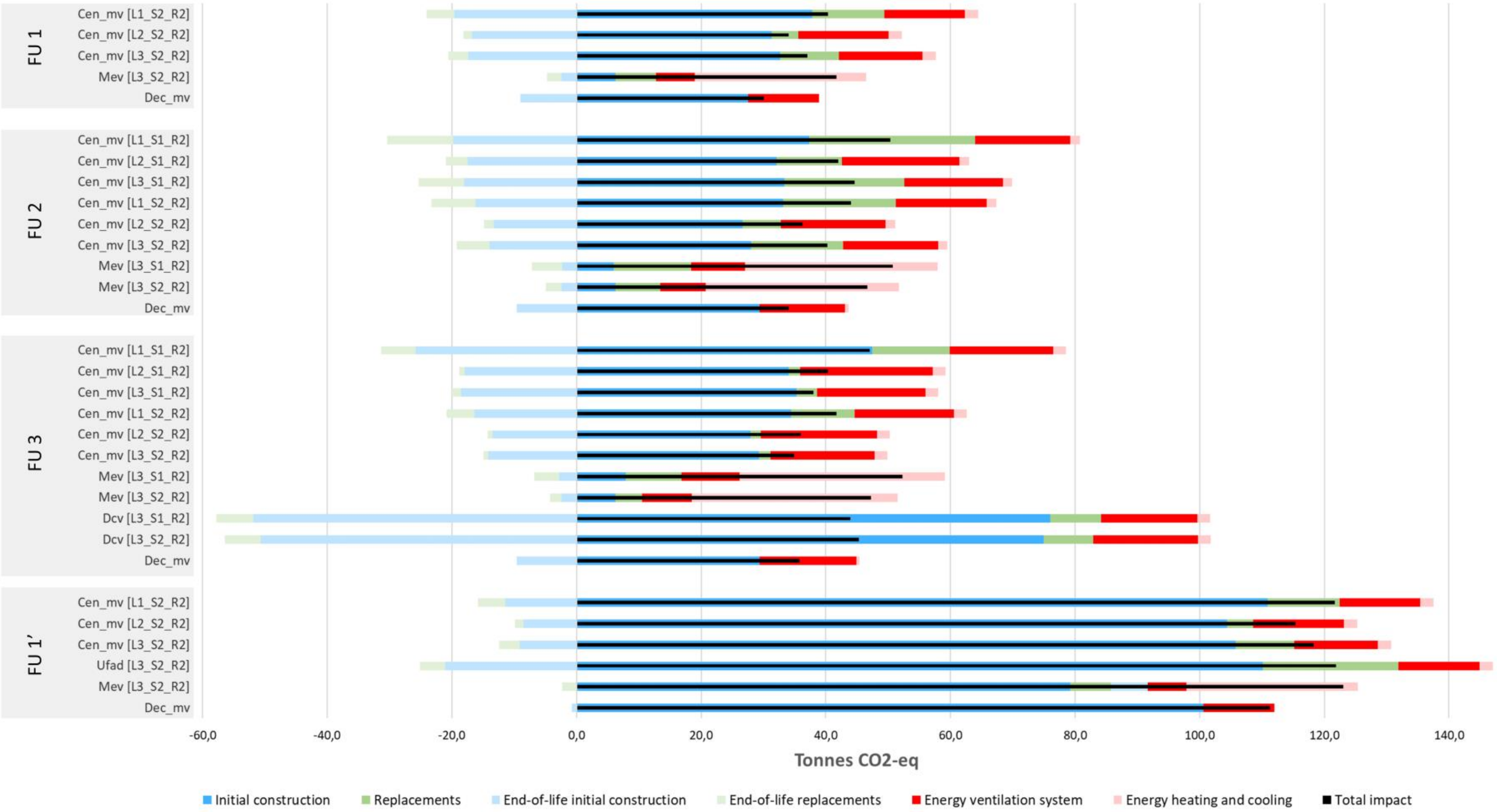


Figure 3. Disaggregated environmental impact ventilation strategies for all functional units. Initial construction = Environmental impact caused by all the materials used for configuration 1; Replacements = Environmental impact caused by all materials which are not initially included in configuration 1.

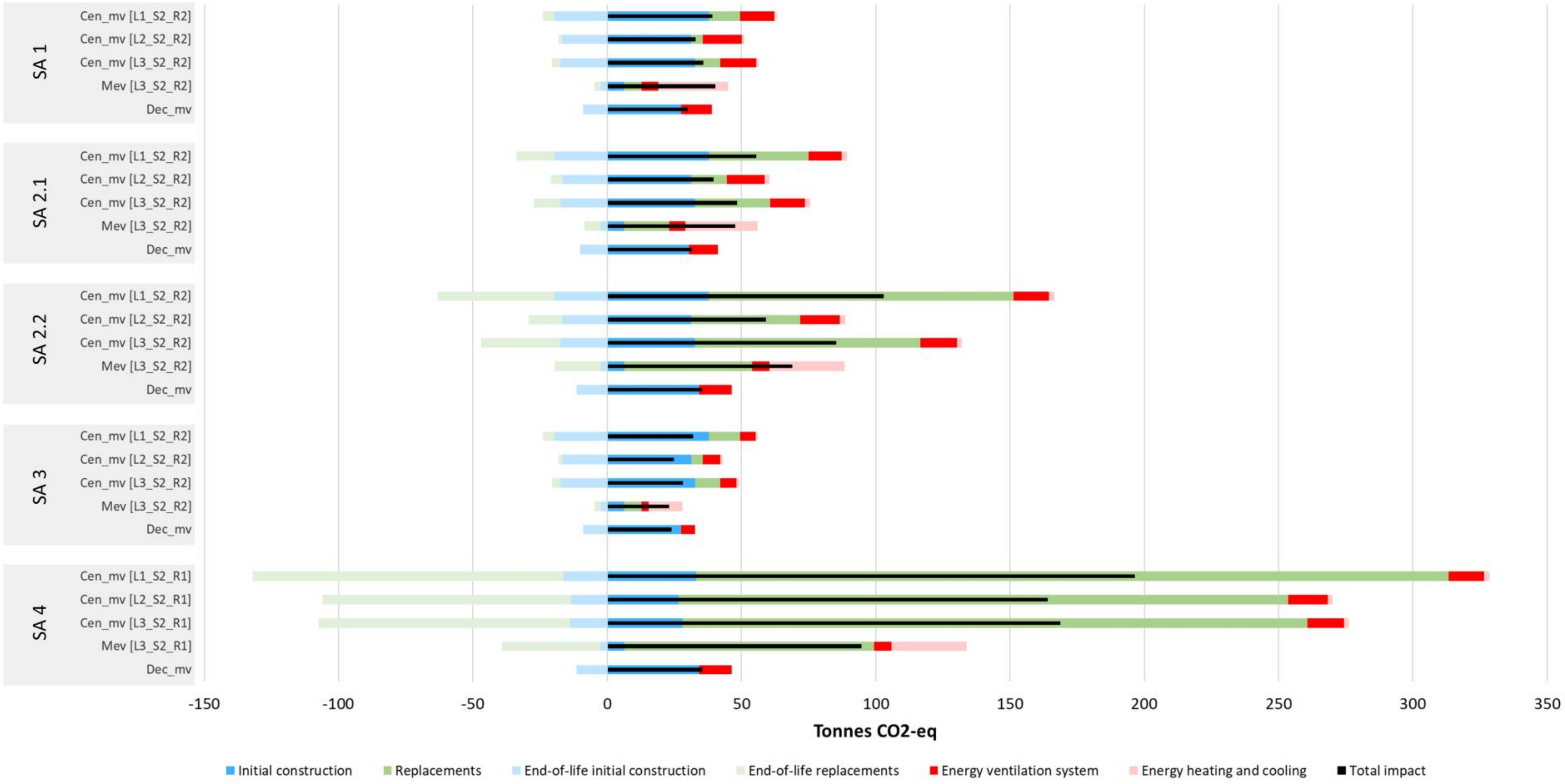


Figure 4. Results sensitivity analyses. Initial construction = Environmental impact caused by all the materials used for configuration 1; Replacements = Environmental impact caused by all materials which are not initially included in configuration 1.

4. Discussion

The present case study contributes to the field of adaptable buildings by comparing the environmental impact of several ventilation strategies in a flexible context. The results show that in this context, material efficient strategies are most likely to have the lowest environmental impact. However, considering the results from the sensitivity analyses, a large range of outcomes is possible. This illustrates the importance of assessing the environmental impact quantitatively to assure well-informed design choices.

To date, almost no case studies exist where the environmental impact of ventilation systems are quantitatively compared to each other in a flexible context. Only one exploratory case study carried out an LCA on a centralized balanced mechanical ventilation system and a ductless mechanical exhaust ventilation system in a school building where the configuration of the floorplan changes every five years [30]. The results from this study show that the impact of centralized mechanical ventilation is 40% higher despite it being more energy efficient. The present case study in this paper distinguishes itself from the exploratory case study in two ways.

First, the design of the ventilation strategies and the LCA are carried out more in depth, using design algorithms and datasets and data collections that are more up to date and data collection to assess the environmental impact. Secondly, the flexible use scenarios are not chosen randomly in this study, but are based on the input by educational stakeholders. The latter is important, given that future building use depends on the needs of relevant stakeholders.

Bearing the innovative character of this study in mind, some novel insights are obtained. While most studies assessing the sustainability of ventilation systems only take the energy consumption into account, e.g. studies from Ben-David and Waring [56] and Amanowicz et al. [57], it turns out that the material-related environmental impact becomes greater, both in absolute and relative terms, in a flexible context. Considering the results from FU 1, it can be deduced that material-related environmental impact accounts for 50 to 63% of the total impact. Only for the mechanical exhaust ventilation the greatest impact, 81%, is caused by energy consumption.

As shown in Figure 1, the material-related environmental impact of the initial construction is approximately equally divided between the ductwork and the air handling unit for the centralized ventilation systems. However, when the configuration changes, only the ductwork requires replacements. This means that ventilation strategies that minimize ductwork usage perform better when a certain degree of adaptability is required.

The only exception is the mechanical exhaust ventilation strategy. Despite its use of few materials, it has the highest environmental impact because this ventilation strategy requires a higher energy demand for heating and cooling compared to other ventilation strategies. In this case, an additional 65,5 MWh is required over a period of 20 years when the school building is equipped with a mechanical exhaust ventilation compared to when a centralized balanced mechanical ventilation system is used. However, the sensitivity analyses show that a mechanical exhaust ventilation system does not have the largest environmental impact per definition. When the configuration of the floorplan layout changes more rapidly, and the material-related impact thus becomes more important, its relative environmental impact decreases. Following the same logic, when the electricity mix has a lower environmental impact, its relative environmental impact decreases as well. On the other hand, using a less energy efficient system than a heat pump will have the opposite effect, resulting in an even higher environmental impact that is related to heating and cooling.

Another observation is that low pressure systems, i.e. diffuse ceiling ventilation and under floor air distribution, are not the most environment friendly solutions despite often being praised for their adaptability [58]. Moreover, diffuse ceiling ventilation is only able to facilitate the first two configurations, strongly limiting its adaptability. However, despite their higher environmental impact, these systems can be more user-friendly as it is easier to remove a floor diffuser than to remove and replace the entire network of ducting. In addition, a raised floor is multifunctional as it can also be used to cover ICT cables for example.

However, it is important to discuss some limitations of this study as well. First, although all ventilation strategies meet the required ventilation standards, they will not lead to the exact same indoor environment. For example, a mechanical exhaust ventilation system leads to more draughts when the wind is strong since air is supplied naturally [59]. Diffuse ceiling ventilation, on the other hand, is able to achieve high levels of thermal comfort [60]. Since it is impossible to take all these differences into account, the ventilation strategies are compared to each other at a conceptual level.

Secondly, it should be stressed that sustainability is more than environmental impact. It also includes economic and social impacts. It is important to emphasize this, since adaptable building solutions often have a higher initial cost, although they might have a lower total cost of ownership [61]. To assess this properly, a life cycle cost analysis (LCCA) can be carried out. An example of such a study carried out by Milwicz and Pasławski [62], where the life cycle cost for several heating systems are compared in a flexible context for a single family building, shows that more sustainable solutions indeed have a higher initial cost, but that their total life cycle cost is lower compared to more polluting heating systems. Besides the environmental and economic impact, it is also important to consider the end-users when designing ventilation systems. When building owners do not know how to optimally manage the ventilation system in a flexible context, potential gains risk being lost.

Future research effort should take these other dimensions of sustainability into account as well, e.g. by conducting an LCCA and a social life cycle assessment (S-LCA) as well as an LCA. In addition, the effect of other types of flexible building usage should be studied. It would, for example, be interesting to look more in-depth into more short-term flexible building usage. In a school context, this can manifest itself in the community being more closely involved in the school building after school hours. This might require other solutions, such as smart controlled ventilation [63]. In this case, it can be expected that the energy-related environmental impact might increase, since more hours of heating, cooling and ventilation would be required. Besides school buildings, other types of buildings, such as office buildings, might also be considered for a flexible building usage. These other building types might also require other ventilation solutions. Finally, studying the role of other technical services in adaptable buildings is also encouraged.

5. Conclusion

To conclude, ventilation must be taken into account when designing a building that is intended for a flexible usage. In this case study, the environmental impact of five ventilation strategies is compared to each other in a school building where configuration of the floorplan changes every five years. Consequential LCA is used to assess the environmental impact. Generally, it can be concluded that the material-related environmental impact increases in a flexible context.

It is found that a decentralized balanced mechanical ventilation systems often has the lowest environmental impact, mainly because few adaptations are required when the configuration of the floorplan changes. This leads to an environmental impact which is 13% lower than the impact of a centralized balanced mechanical ventilation. A mechanical exhaust ventilation system has the highest environmental impact despite its low material usage. This is explained by the large energy demand for heating and cooling that accompanies this ventilation strategy, resulting in an environmental impact which is 38% higher than the impact of decentralized balanced mechanical ventilation system. However, when the configuration of the floorplan changes more rapidly or a cleaner electricity mix is used, its relative environmental impact decreases. This shows the necessity of making informed prognoses about possible future use when designing the ventilation system. Regarding the ductwork for the centralized balanced mechanical ventilation system, it is recommended in a flexible context to use as few materials as possible instead of oversizing the dimensions to increase the energy efficiency as this can reduce the environmental impact by 16%. Moreover, it is found that distributing the ductwork over two shafts increases the potential to use a building flexibly while at the same time reducing the environmental impact by 14% since smaller dimensions of ductwork can be used. The low-pressure ventilation systems, i.e. diffuse ceiling ventilation systems and under floor air distribution, have been shown to have a larger environmental impact, respectively 26% and 6%, than a standard centralized balanced mechanical ventilation system.

Bearing these insights in mind, further research should also look into other types of flexible building usage and account for life cycle costing as well.

6. Supplementary material

Supplementary data to this article can be found online:
https://data.mendeley.com/datasets/3rsxdxvy8k/1

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Bibliography

[1] Ö. Çimen, Construction and built environment in circular economy: A comprehensive literature review, J Clean Prod. 305 (2021). https://doi.org/10.1016/j.jclepro.2021.127180.

[2] Ellen MacArthur Foundation, Delivering the circular economy: a toolkit for policymakers, 2015.

[3] L. Belussi, B. Barozzi, A. Bellazzi, L. Danza, A. Devitofrancesco, C. Fanciulli, M. Ghellere, G. Guazzi, I. Meroni, F. Salamone, F. Scamoni, C. Scrosati, A review of performance of zero energy buildings and energy efficiency solutions, Journal of Building Engineering. 25 (2019) 100772. https://doi.org/10.1016/j.jobe.2019.100772.

[4] J. O'Connor, Survey on actual service lives for North American buildings, in: Woodframe Housing Durability and Disaster Issues Conference, Las Vegas, 2004.

[5] R. Askar, L. Bragança, H. Gervásio, Adaptability of buildings: A critical review on the concept evolution, Applied Sciences (Switzerland). 11 (2021). https://doi.org/10.3390/app11104483.

[6] B.E. Ross, D.A. Chen, S. Conejos, A. Khademi, Enabling Adaptable Buildings: Results of a Preliminary Expert Survey, Procedia Eng. 145 (2016) 420–427. https://doi.org/10.1016/j.proeng.2016.04.009.

[7] J. Gosling, P. Sassi, M. Naim, R. Lark, Adaptable buildings: A systems approach, Sustain Cities Soc. 7 (2013) 44–51. https://doi.org/10.1016/j.scs.2012.11.002.

[8] S. Conejos, C. Langston, J. Smith, Designing for better building adaptability: A comparison of adaptSTAR and ARP models, Habitat Int. 41 (2014) 85–91. https://doi.org/10.1016/j.habitatint.2013.07.002.

[9] K. Wang, S. De Regel, W. Debacker, J. Michiels, J. Vanderheyden, Why invest in a reversible building design?, in: IOP Conf Ser Earth Environ Sci, 2019. https://doi.org/10.1088/1755-1315/225/1/012005.

[10] O. Heidrich, J. Kamara, S. Maltese, F. Re Ceccione, A critical review of the developments in building adaptability, International Journal of Building Pathology and Adaption. 35 (2017) 284–303.

[11] G. Safarzadeh, Agility, Adaptability + Appropriateness: Conceiving, Crafting & Constructing an Architecture of the 21st Century, ARCC. 9 (2012).

[12] R.P. Geraedts, Design for Change; Flexibility Key Performance Indicators, in: 1st International Conference on Industrialised, Integrated, Intelligent Construction (I3CON), 2008: p. 11.

[13] E.K. Julistiono, N. Hosana, F. Liemansetyo, I.F. Wijaya, Spatial and Structural Aspects of an Adaptable Building, DIMENSI (Journal of Architecture and Built Environment). 44 (2017) 87–94. https://doi.org/10.9744/dimensi.44.1.87-94.

[14] R. Geraedts, FLEX 4.0, A Practical Instrument to Assess the Adaptive Capacity of Buildings, in: Energy Procedia, The Author(s), 2016: pp. 568–579. https://doi.org/10.1016/j.egypro.2016.09.102.

[15] O. Seuntjens, B. Belmans, M. Buyle, A. Audenaert, A critical review on the adaptability of ventilation systems : Current problems , solutions and opportunities, Build Environ. 212 (2022) 108816. https://doi.org/10.1016/j.buildenv.2022.108816.

[16] H. Estaji, A Review of Flexibility and Adaptability in Housing Design, International Journal of Contemporary Architecture. 4 (2017) 37–49. https://doi.org/10.14621/tna.20170204.

[17] E. Durmisevic, Transformable Building Structures: Design for disassembly as a way to introduce sustainable engineering to building design & construction, Technische Universiteit Delft, 2006.

[18] N. Rajagopalan, S. Brancart, S. De Regel, A. Paduart, N. De Temmerman, Multi-Criteria Decision Analysis Using Life Cycle Assessment and Life Cycle Costing in Circular Building Design : A Case Study for Wall Partitioning Systems in the Circular Retrofit Lab, Sustainability. 13 (2021). https://doi.org/https://doi.org/10.3390/.

[19] C. Cavalliere, G.R. Dell’Osso, F. Favia, M. Lovicario, BIM-based assessment metrics for the functional flexibility of building designs, Autom Constr. 107 (2019). https://doi.org/10.1016/j.autcon.2019.102925.

[20] Z. De Simone, T. Zheng, T.B. Xu, S. Kalantari, FlexiArch: A computational tool to assess the longevity of buildings through flexibility, Journal of Building Engineering. 78 (2023) 107178. https://doi.org/10.1016/j.jobe.2023.107178.

[21] L. Valli, A. Stefanski, R. Jacobson, Typologizing School–Community Partnerships: A Framework for Analysis and Action, Urban Educ (Beverly Hills Calif). 51 (2016) 719–747. https://doi.org/10.1177/0042085914549366.

[22] P. Barrett, A. Treves, T. Shmis, D. Ambasz, M. Ustinova, The Impact of School Infrastructure on Learning: A Synthesis of the Evidence, The World Bank, 2019.

[23] R. Kronenburg, Flexible: Architecture that Responds to Change, Laurence King Publishing Ltd, London, 2007.

[24] D.M. Gann, J. Barlow, Flexibility in building use: The technical feasibility of converting redundant offices into flats, Construction Management and Economics. 14 (1996) 55–66. https://doi.org/10.1080/01446199600000007.

[25] M.M. Ouf, W. O'Brien, B. Gunay, On quantifying building performance adaptability to variable occupancy, Build Environ. 155 (2019) 257–267. https://doi.org/10.1016/j.buildenv.2019.03.048.

[26] R. Phillips, L. Troup, D. Fannon, M.J. Eckelman, Do resilient and sustainable design strategies conflict in commercial buildings? A critical analysis of existing resilient building frameworks and their sustainability implications, Energy Build. 146 (2017) 295–311. https://doi.org/10.1016/j.enbuild.2017.04.009.

[27] L. Pérez-Lombard, J. Ortiz, C. Pout, A review on buildings energy consumption information, Energy Build. 40 (2008) 394–398. https://doi.org/10.1016/j.enbuild.2007.03.007.

[28] M.L. Fong, Z. Lin, K.F. Fong, V. Hanby, R. Greenough, Life cycle assessment for three ventilation methods, Build Environ. 116 (2017) 73–88. https://doi.org/10.1016/j.buildenv.2017.02.006.

[29] ISO 14044:2006 Environmental management — Life cycle assessment — Requirements and guidelines, 2006.

[30] O. Seuntjens, B. Belmans, M. Buyle, Z. Kabbara, S. Jorens, A. Audenaert, Should we ventilate differently in an adaptable context ? An exploratory LCA-study ., in: REHVA 14th HVAC World Congress, CLIMA, Rotterdam, 2022.

[31] M. Buyle, W. Galle, W. Debacker, A. Audenaert, Sustainability assessment of circular building alternatives: Consequential LCA and LCC for internal wall assemblies as a case study in a Belgian context, J Clean Prod. 218 (2019) 141–156. https://doi.org/10.1016/j.jclepro.2019.01.306.

[32] J. Pinder, R. Schmidt, J. Saker, Stakeholder perspectives on developing more adaptable buildings, Construction Management and Economics. 31 (2013) 440–459. https://doi.org/10.1080/01446193.2013.798007.

[33] O. Seuntjens, M. Buyle, B. Belmans, A. Audenaert, Unlocking the Full Sustainability Potential of School Buildings by Reconciling Building Properties with Educational and Societal Needs, Sustainability. 14 (2022).

[34] Vlaams energie- en klimaatagentschap, EPB-eisen bij bouwaanvraag/melding in 2022, (2022). https://www.vlaanderen.be/epb-pedia/epb-plichtig-toepassing-en-eisen/epb-eisentabellen-per-aanvraagjaar/epb-eisen-bij-bouwaanvraag-melding-in-2022 (accessed June 14, 2023).

[35] ASHRAE, Ventilation for Acceptable Indoor Air Quality, 2019.

[36] A.F. Alajmi, H.Z. Abou-Ziyan, W. El-Amer, Energy analysis of under-floor air distribution (UFAD) system: An office building case study, Energy Convers Manag. 73 (2013) 78–85. https://doi.org/10.1016/j.enconman.2013.04.003.

[37] W. Wu, N. Yoon, Z. Tong, Y. Chen, Y. Lv, T. Ærenlund, J. Benner, Diffuse ceiling ventilation for buildings: A review of fundamental theories and research methodologies, J Clean Prod. 211 (2019) 1600–1619. https://doi.org/10.1016/j.jclepro.2018.11.148.

[38] Z. Kabbara, S. Jorens, H. Matbouli, J. Van Thillo, I. Verhaert, Energy & Buildings Heuristic optimization for designing centralized air distribution systems in non-residential buildings, Energy Build. 292 (2023) 113161. https://doi.org/10.1016/j.enbuild.2023.113161.

[39] S. Jorens, I. Verhaert, K. Sörensen, Design optimization of air distribution systems in non-residential buildings, Energy Build. 175 (2018) 48–56. https://doi.org/10.1016/j.enbuild.2018.07.018.

[40] ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework, 2006.

[41] B.P. Weidema, T. Ekvall, R. Heijungs, Guidelines for application of deepened and broadened LCA: Deliverable D18 of work package 5 of the CALCAS project, 2009.

[42] M. Buyle, J. Braet, A. Audenaert, Life cycle assessment in the construction sector: A review, Renewable and Sustainable Energy Reviews. 26 (2013) 379–388. https://doi.org/10.1016/j.rser.2013.05.001.

[43] Worldsteel Association, 2023: World Steel in Figures, 2023.

[44] International Aluminium, 2019 Life Cycle Inventory (LCI) Data and Environmental Metrics, 2022.

[45] M. Buyle, J. Braet, A. Audenaert, W. Debacker, Strategies for optimizing the environmental profile of dwellings in a Belgian context: A consequential versus an attributional approach, J Clean Prod. 173 (2018) 235–244. https://doi.org/10.1016/j.jclepro.2016.08.114.

[46] W.C. Lam, D. Trigaux, Environmental profile of buildings, 2021.

[47] CIBSE, Maintenance engineering and management: Indicative economic life expectancy, 2020.

[48] O. Ortiz, F. Castells, G. Sonnemann, Sustainability in the construction industry: A review of recent developments based on LCA, Constr Build Mater. 23 (2009) 28–39. https://doi.org/10.1016/j.conbuildmat.2007.11.012.

[49] M. Buyle, B. Maes, S. Van Passel, K. Boonen, A. Vercalsteren, A. Audenaert, Ex-ante LCA of emerging carbon steel slag treatment technologies: Fast forwarding lab observations to industrial-scale production, J Clean Prod. 313 (2021) 127921. https://doi.org/10.1016/j.jclepro.2021.127921.

[50] EN 15804 Sustainability of construction works -Environmental product declarations – Core rules for the product category of construction products, 2012.

[51] Y. Asiedu, R.W. Besant, P. Gu, HVAC duct system design using genetic algorithms, HVAC and Research. 6 (2000) 149–173. https://doi.org/10.1080/10789669.2000.10391255.

[52] D. Ramon, K. Allacker, F. De Troyer, H. Wouters, N.P.M. van Lipzig, Future heating and cooling degree days for Belgium under a high-end climate change scenario, Energy Build. 216 (2020) 109935. https://doi.org/10.1016/j.enbuild.2020.109935.

[53] V.M. Nik, Making energy simulation easier for future climate–Synthesizing typical and extreme weather data sets out of regional climate models (RCMs), Appl Energy. 177 (2016) 204–226.

[54] A. De Vita, P. Capros, L. Paroussos, EU Reference Scenario 2020 - Energy transport and GHG emissions, Brussel, 2021.

[55] G. Luderer, M. Leimbach, N. Bauer, E. Kriegler, L. Baumstark, Description of the REMIND model (Version 1.6), 2015.

[56] T. Ben-David, M.S. Waring, Impact of natural versus mechanical ventilation on simulated indoor air quality and energy consumption in offices in fourteen U.S. cities, Build Environ. 104 (2016) 320–336. https://doi.org/10.1016/j.buildenv.2016.05.007.

[57] Ł. Amanowicz, K. Ratajczak, E. Dudkiewicz, Recent Advancements in Ventilation Systems Used to Decrease Energy Consumption in Buildings—Literature Review, Energies (Basel). 16 (2023) 1–39. https://doi.org/10.3390/en16041853.

[58] A. Alajmi, W. El-Amer, Saving energy by using underfloor-air-distribution (UFAD) system in commercial buildings, Energy Convers Manag. 51 (2010) 1637–1642. https://doi.org/10.1016/j.enconman.2009.12.040.

[59] M.K. Fageha, A. Alaidroos, Performance Optimization of Natural Ventilation in Classrooms to Minimize the Probability of Viral Infection and Reduce Draught Risk, Sustainability (Switzerland). 14 (2022). https://doi.org/10.3390/su142214966.

[60] C.A. Hviid, S. Svendsen, Experimental study of perforated suspended ceilings as diffuse ventilation air inlets, Energy Build. 56 (2013) 160–168. https://doi.org/10.1016/j.enbuild.2012.09.010.

[61] C. Martani, L. Cattarinussi, B.T. Adey, A new process for the evaluation of the net-benefit of flexible ground-floor ceiling in the face of use transition uncertainty. The application case of an office building in London, Journal of Building Engineering. 15 (2018) 156–170. https://doi.org/10.1016/j.jobe.2017.11.019.

[62] R. Milwicz, J. Pasławski, Comparative analysis of heating systems in terms of flexibility in sustainable buildings, in: Procedia Eng, Elsevier B.V., 2017: pp. 82–89. https://doi.org/10.1016/j.proeng.2017.11.024.

[63] B. Merema, D. Saelens, H. Breesch, Analysing modelling challenges of smart controlled ventilation systems in educational buildings, J Build Perform Simul. 14 (2021) 116–131. https://doi.org/10.1080/19401493.2020.1867639.