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A critical review on the adaptability of ventilation systems: current problems, solutions and opportunities

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Abstract

At present many buildings, that are not able to meet the changing needs of owners and users, are demolished before they reach their technical lifespan. To avoid such waste, the construction industry is shifting to adaptable building practices. Comfort systems in buildings that can effectively deal with an adaptable context are critical to the success of this transition. After all, these systems must ensure that the health and comfort of occupants is guaranteed in all possible flexibility scenarios. In practice, comfort systems that provide ventilation strongly adhere to firmly rooted approaches with limited adaptability. Moreover, implementing adaptability does not happen at the conceptual level, but is achieved by oversizing components and incorporating demand control. Alternative ventilation systems that are conceptually more compatible with an adaptable context are rarely even considered. To fill this knowledge gap, this review article identifies and uses various adaptability characteristics of ventilation systems to qualify both contemporary and innovative ventilation systems based on their ability to facilitate a flexible building use. By juxtaposing the systems, the article goes beyond the state-of-the-art and learns from the meta-level rather than individual cases. It is concluded that traditional ventilation strategies do not provide the most appropriate solution for an adaptive context, that bulky ductwork is incompatible with long-term flexible building use, and that specific guidelines for designing adaptable ventilation systems are lacking. Further research should look into this and additionally quantify the environmental and financial benefits of adaptable ventilation systems through life cycle assessment and life cycle cost evaluation.

Key words: Ventilation, Adaptable buildings, Circularity, Design strategies, Flexible usage, Life cycle thinking

Highlights:

- *Specific guidelines to design adaptable ventilation systems are lacking*
- *Voluminous ductwork is not compatible with a long-term flexible building usage*
- *Innovative ventilation strategies have a potential in terms of adaptability*
- *LCA & LCCA should be carried out to quantify the impacts in the design phase*

1. Introduction

Over the past decade, there has been a strong focus on reducing the environmental impact of the construction sector to meet the targets set out in the Paris agreement [1]. At the building level, the focus typically lies on improving energy efficiency by increasing insulation levels, increasing air tightness and incorporating more efficient technical installations [2–4]. Because buildings are becoming increasingly energy efficient [5], the share of material-related environmental impacts has gained importance, both in absolute and relative terms [6]. To reduce the material-related impact, the circular economy advocates using all materials and components to their maximum value [7]. In this respect, there is a strong need for buildings to be more adaptable in order to allow for flexible use and reuse of building components. By pursuing this rationale, the construction industry can contribute to a more sustainable future with less waste and emissions.

Two categories of flexibility can be distinguished: the degree of need for adaptability over time (i.e. long term or short term flexibility) and the requirement to alter the floorplan layout to meet changing user demands. Long term flexibility refers to the potential to adapt to activities that are only carried out after a significant amount of time, e.g. large refurbishments. Short term flexibility, on the other hand, involves facilitating rapid adjustments that can take place even in a single day. E.g. in a school context, short term flexibility can stimulate a more extensive building use if school infrastructure can be used for purposes other than education outside of school hours. Finally, adaptable buildings should also allow for the reconfiguration of the floorplan layout, after a shorter as well as a longer period of time. In the short term, this can be facilitated by using moveable or demountable and reusable walls. In the long term, a reconfiguration of the floorplan layout can occur during larger refurbishments. A case study carried out by Wang et al. [8] showed that it is financially beneficial to invest in a commercial office building where the floorplan layout can be easily reconfigured since this reduces the risk of vacancy with corresponding loss of income.

Today much of our building stock is not yet designed with the need for adaptability in mind. O'Connor [9] surveyed the reason why 227 buildings in North America were demolished. Only eight buildings were torn down because their technical lifespans had been reached. All other buildings were dismantled prematurely, mainly because they could not meet evolving needs. These evolving needs can vary [10–12]. To avoid this much building waste, buildings must be designed bearing adaptability in mind. The current state-of-the-art concerning adaptable buildings mainly focuses on smart spatial configurations [13–15] and the oversizing of building components to avoid future lock-in effects [16,17]. However, especially when buildings are used in a flexible manner, compatible comfort systems must also be in place to ensure healthy and comfortable indoor environments at all times under all possible flexibility scenarios. This is clearly underscored by the Covid-19 pandemic, where experts recommended intensive ventilation, but many buildings lack the adaptability potential to robustly achieve the necessary air changes. In this regard, HVAC designers face a new challenge. Instead of considering fixed design requirements that change little over a building's lifetime, ventilation systems should take the entire building life cycle in mind, balancing varying requirements for health, comfort and energy efficiency and life cycle costs [18,19].

Contemporary ventilation systems still adhere strongly to established approaches. However, these approaches are not designed for an adaptable context. Therefore, it is likely that alternative ventilation systems can better address the need for adaptability. When looking at the long term, the lifespan of ventilation systems is considerably shorter than the lifespan of buildings in general. Based on the Brand model [20] and similar models [21,22], technical services have always been included as a separate layer and their lifespan is often estimated between 7 and 15 years [23,24]. Nevertheless, the technical lifespan of ventilation systems has also been estimated to be 25 years by Durmisevic [25], which is substantially longer. Regardless of what the actual life span of a ventilation system is - which will depend heavily on exactly how you define a 'system' - the components should be easy to replace and should not hinder large refurbishments. Not only after, but also within the lifespan of ventilation systems a certain degree of adaptability is required. When (part of) a building is being used in a flexible way, this may lead to fluctuating ventilation requirements as well. The occupancy rate, floorplan layout [26] and function [27,28] of a building are three examples of factors that may change rather rapidly over time and have an impact on the required ventilation rate [29,30].

Yet, in many cases ventilation systems have proven to be unsuitable to cope with the fluctuating requirements [31,32]. Traditional ventilation solutions, where it is advised to sufficiently overdimension the ventilation system, are often incompatible with a flexible context in an efficient way. Large ductwork is often incompatible with the use of the demountable and reusable walls that are available on the market and make it possible to reconfigure the floorplan layout of a building [33,34]. When these walls are penetrated by ductwork, it becomes difficult to reuse these walls afterwards. Moreover, the penetrations can cause issues regarding acoustics and fire safety. Additionally, the level to which a building can be reconfigured can be constrained by the amount and the position of the inlets and outlets. In addition, following the fan affinity laws, presuming that other factors remain unchanged, an exponential increase in energy consumption will occur if the fan is not dimensioned with respect to future scenarios where a higher ventilation rate is required [35]. This lack of adequate knowledge regarding the link between adaptability and ventilation limits the possibilities of using buildings in a healthy, flexible and thus sustainable way.

Other review studies have focused on the adaptability of buildings in general [18,27] and the performances of ventilation systems in terms of indoor air quality and energy efficiency [36] and their categorization [37]. There is, however, a knowledge gap about how to incorporate ventilation systems in adaptable buildings in a sustainable way. This review paper focusses on the compatibility of contemporary ventilation strategies within an adaptive context. Firstly, the methodology used is discussed. Secondly a wide range of proposed measures and guidelines that increase the adaptability of ventilation systems is discussed. In the next section, five ventilation strategies are discussed that include some of these adaptability characteristics. Also their potential in allowing for a flexible usage is analyzed. Afterwards, in the discussion section, problems are identified and existing solutions and opportunities are explored. The concluding section summarizes the main findings of this research.

2. Material and methods

The aim of this review paper is to critically review the current state-of-the-art regarding the link between adaptability and ventilation, to highlight research gaps and to propose recommendations for further research by answering following research questions:

1. What are the needs and barriers for ventilation systems in an adaptable building context?
2. What are the proposed measures by the state-of-the-art to increase the adaptability of ventilation systems?
3. Which ventilation strategies already include some of these proposed measures, how do they allow for a flexible usage and what are their boundary conditions?
4. Based on the identified research gaps, what are opportunities for further research (technical solutions, building management, legislation, …)?

Web of Science and Google Scholar were used as bibliographic database. After a first screening on the keywords ‘adaptable buildings’, ‘flexible buildings’, ‘flexible ventilation’ and ‘flexible technical services’ a range of sources was retained in the form of papers, theses, assessment tools and technical guidelines. After analyzing these sources, and the sources to which they referred, a selection was made of sources that discussed adaptable buildings in general and sources that discussed ventilation systems, or technical services as a whole, in terms of adaptability.

The first research question is answered by analyzing standards about ventilation requirements and general papers about adaptable buildings and their characteristics. To answer the second research question, an overview was made of 25 sources that propose measures and guidelines for ventilation systems to allow for a more flexible usage. However, among these 25 sources there are only 7 that discuss ventilation systems in particular. The other sources discuss technical services in general. From all the retrieved measures and guidelines, five subcategories are made in which all of the measures and guidelines were divided: accessibility, oversizing, distribution, controllability and technical circularity. The result of this overview is given in Table 1. It is analyzed how these measures and guidelines can be adopted for ventilation systems specifically.

For the third research question, the proposed measures and guidelines that were found in the literature review will be tested against current existing ventilation strategies. Five ventilation strategies were found that include some of the measures and guidelines that are summarized in Table 1. The boundary conditions from these strategies will be discussed and it will be analyzed to which extent these strategies have the potential to allow for short term flexibility, long term flexibility and the reconfiguration of the floorplan layout. An overview of this comparison can be found in Table 2.

Finally in the discussion, based on the review of the state-of-the-art, the last research question will be answered. It will be analyzed which research gaps in terms of adaptable ventilation still hinder a flexible usage. Recommendations for further research will be formulated to overcome the discussed shortcomings.

3. Characteristics of adaptable ventilation systems

Adequate ventilation is essential for the health and comfort of building occupants [38]. As buildings have become more air-tight over recent years, but also because of the Covid-19 pandemic, minimum ventilation rates have become more strict [39–41]. To answer these minimum ventilation requirements, a wide range of ventilation strategies can be adopted. These strategies can go from fully natural to fully mechanical.

Besides ensuring a healthy indoor environment, ventilation systems should be adaptable in order to allow for a flexible usage. In this section, characteristics of adaptability that concern ventilation systems will be discussed. In Table 1, an overview is given of proposed measures and guidelines by several authors, that are all subdivided in five subcategories. Since the majority of these recommendations concern technical services as a whole, it will be analyzed how these measures and guidelines can be adopted for ventilation systems in particular.

3.1. Accessibility

Ventilation systems, just like other technical services, should be accessible for several reasons. Firstly, it is important to regularly change the filters and clean the ductwork, in order to ensure the supply of clean outdoor air [42]. A list of all maintenance tasks and their corresponding frequency can be found in the ASHRAE standard 62.1 [29]. Secondly, as the lifespan of components from ventilation systems is shorter than the lifespan of the entire building, these components need to be replaced after a period of time [25,43,44]. To facilitate this maintenance and refurbishments, a good accessibility is crucial [45].

An often cited model is the layering model, which is shown in Figure 1. This model states that layers with different lifespans should be physically separated from each other, so that when a certain layer needs to be replaced or maintained, other layers will remain undamaged [20]. This concept can be found in assessment tools such as Flexis, which is an assessment tool that quantifies the adaptability of technical installations. The Flexis tool states that in order to enhance the adaptability of technical installations, it is best to keep the technical components in the infill level instead of integrating them in structural elements [46]. For ventilation systems specifically, this principle is mainly relevant for the air distribution network. In daily practice, it still occurs regularly that the air distribution network of the ventilation system is integrated in the floor slab of a building. If the ductwork needs to be replaced or serviced, it is impossible to do so without damaging the floor slab as well. To avoid these problems, it is advised by Gosling et al. [23], Nakib [47] and Fuster et al. [48] to use lowered ceilings, plenums, raised floors or central cores. Besides completely integrating technical services, Geraedts [33] and Israelsson and Hansson [49] stress avoiding penetrations between technical services and structural elements. Also this is mainly relevant for the air distribution network, as ductwork can penetrate walls or beams that support the floor slab. This can also be solved by using lowered ceilings or raised floors, but the disadvantage of this is that it can significantly reduce the free floor-to-floor height, which is also an important parameter in terms of adaptability [18]. Furthermore, Zivkovic and Jovanovic [50] and Cavalliere et al. [51] suggest grouping technical services, such as air handling units, in an easily accessible location such as rooftops or in a centrally positioned technical core. In order to make sure that it is clear for both building users, who often lack technical knowledge, and construction professionals how to access the ventilation system, OVAM [52] advises to develop a user's guide and video report that shows how the ventilation systems can be accessed.

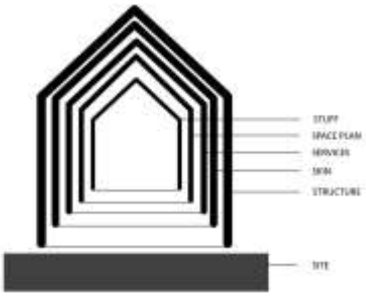


Figure 1. Layering model [20]

3.2. Oversizing

Another recommendation is to oversize technical services in order to accommodate growing and evolving demands in the future [52,53]. In terms of ventilation, oversizing refers to the capacity of the distribution network to distribute air and the maximum air flow rate that can be generated by the fans. The Flexis assessment tool argues that to anticipate future scenarios, both the power capacity of technical services as well as the dimensions of the distribution network should be overdimensioned with a surplus, based on the current needs, between 50 and 100% [46]. Concerning the oversizing of the maximum air flow rate in the case of natural ventilation, this can be achieved by using a sufficient amount of openable windows and vents. When it comes to mechanical ventilation, a greater air flow can be foreseen by using fans that have a the capacity to generate a higher maximum air flow.

Oversizing the distribution network of ventilation systems depends on which kind of distribution network is applied. In the case of a traditional mechanical ventilation system where ductwork is used to distribute the air, the dimensions of this ductwork can be designed to create a bigger hydraulic diameter which in turn has a greater capacity to distribute air. However, oversized ductwork requires the use of extra raw materials, resulting in a higher initial environmental and financial impact. Instead of using voluminous ductwork, another solution to distribute air is to use a plenum, which by design has a large capacity to distribute air.

3.3. Distribution

The distribution network of technical services plays an important factor as well in terms of adaptability. This is also valid for ventilation systems, as the kind of air distribution network that is used is linked to the possibilities of reconfiguring the floorplan layout of a building. It is therefore recommended by Scuderi [54] to base the design of the air distribution network not solely on the current configuration, but also on possible future configurations.

First of all, it is stated by Sprengers [34], Geraedts [46] and Nakib [47] that the absence of a physical distribution network is desirable for increased adaptability. A fully natural ventilation which does not use ductwork, facilitates a reconfiguration better since the ductwork will not hinder the use of demountable and reusable walls. However, it is important that an adequate air flow is guaranteed for multiple configurations, for example by using sufficient inlets. Moreover, problems regarding penetrations between ductwork and structural components are avoided as well with natural ventilation. Yet, the problem remains that the drivers behind fully natural ventilation systems are uncontrollable. As a result healthy indoor environments cannot be guaranteed at all times.

When it comes to fully mechanical ventilation systems, where it is possible to control the air flow, there are two possible ways to distribute the air. The distribution of the air can be either centralized or decentralized. A centralized ventilation system uses one central air handling from which the air is distributed over the entire building. As can be seen in Figure 2, this kind of air distribution uses more ductwork than a decentralized ventilation system. This can make it difficult to reconfigure the building, either because the ductwork is imbedded in structural components or because the large ductwork limits the use of demountable and reusable walls that make it possible to reconfigure a building. Therefore it is advised by Netwerk Architecten Vlaanderen [55] to provide a great amount of inlets and outlets in the first design. However, an extensive network of ventilation ducts can cause a significant amount of pressure drops which leads to a higher energy consumption by the fans [56].

A decentralized ventilation system, consists of multiple smaller air handling units that distribute the air to one or only a few rooms. As a result, there is almost no ductwork needed for this kind of ventilation, or at least much less compared with a centralized ventilation system. If after a period of time the building is being reconfigured, additional air handling units can be placed to facilitate the new configuration. A disadvantage of decentralized ventilation systems is that they have a shorter lifespan, approximately 8 to 10 years, compared to 15 years for centralized ventilation systems which is stated by Bhatia [57].

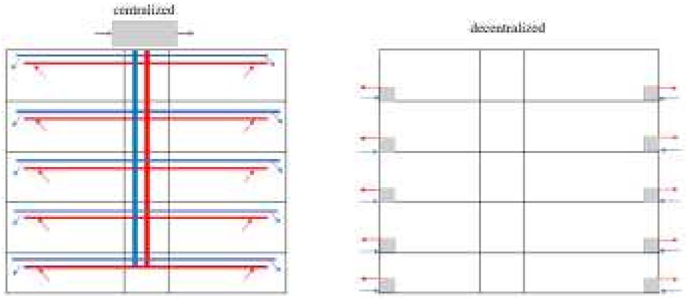


Figure 2. Comparison of central and decentralized ventilation system [58]

3.4. Controllability

To which extent technical services can be controlled is linked to their adaptability as well, since ventilation requirements can vary and fluctuate for different parts of a building. The normative ventilation rate can fluctuate, e.g. by a fluctuating occupancy rate or a change of function, which makes it possible that in some parts of a building a higher air flow is required than in others. Therefore, it is important that ventilation systems can be controlled at the local level and not only centrally [31,46].

This is difficult for fully natural ventilation systems, since this kind of ventilation can by definition hardly be controlled. For mechanical ventilation systems however, it is possible to manage the air flow at the local level, but measures must be taken. OVAM [52] proposes applying demand controlled ventilation (DCV) instead of a constant air flow rate. With DCV, the air flow rates are based on a measurement of the IAQ and/or on a thermal comfort parameter [59]. So when for example there are only a few people present in a room, the air flow rate will be reduced. Conversely, when more people are present, a higher air flow rate will be generated. It has been stated by Merema et al. [59] that DCV has a high energy saving potential for rooms with a varying occupancy profile, both in size and time, such as landscape offices and lecture rooms. For example, in a case study carried out by Sun et al. [60] on a high-rise office building in Hong Kong, it has been found that DCV could save up to 52% energy that is needed for the fans compared to a ventilation system which uses a constant flow rate. Also, in colder climates DCV has the potential to save a significant amount of energy. In two Norwegian schools, Wachenfeldt et al. [61] compared DCV with a ventilation system that uses a constant air flow during a week in November. It was found by measurements and simulations that, compared to the constant air flow rate, the fan energy consumption was reduced by 87% and that the energy demand for heating was reduced by 21% using DCV.

If the ventilation systems is also used to control the temperature of the building, heating and cooling coils are required in the supply duct of every ventilated room. This allows people to adjust the temperature for each room individually. Another possibility is to use an air buffer, for example by making a room bigger, when more people enter that room. This will result in a slower raise in concentration of CO_2.

3.5. Technical circularity

Finally, as shown in Table 1, authors in the field of adaptability and circularity also advocate designing technical services in a modular way so that the components are demountable and can be reused afterwards. This can increase the adaptability of ventilation systems, since adjustments can be made, e.g. replacing or adding certain parts to the distribution network to facilitate a new configuration, without replacing the entire ventilation system. This can be achieved by using components that can be easily and safely disconnected, removed or repositioned [47]. For example, a plug-and-play system can be installed for fans so that a fan can be easily replaced when its lifespan has been reached or when a fan is needed with a higher maximum air flow. Furthermore, it is also advised by Lützkendorf [62] and Webb et al. [63] to use components that can be reused in order to maximize the value of these components. A stepwise procedure, shown in Figure 3, was developed by Mysen et al. [64] that can be followed to decide whether to reuse ductwork or not.

However, sometimes certain components reach the end of their lifespan and need to be replaced. In order to do this without having to replace the entire ventilation system, it is advised to use standardized components that can be easily replaced [65–67]. According to Flexis assessment tool, at least three quarters of a technical service, should be standardized if one wants to increase its adaptability [46].

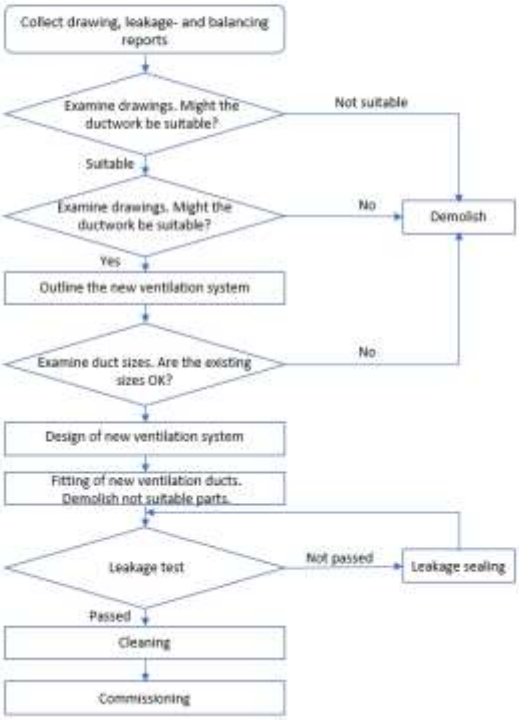


Figure 3. Stepwise procedure for the reuse of ductwork developed by Mysen et al. [64]

Table 1. Summary of state-of-the-art measures and guidelines to improve the adaptability of ventilation systems. Legend of symbols and abbreviations: - = Not discussed; -/+ = Briefly discussed; + = Thoroughly discussed; TS = Technical services; VS = Ventilation systems; CP = Conference paper; JP = Journal paper; RP = Review paper; Tech. report = Technical report; ✓ = Included

Author(s)	*Topic of guideline*					*Discussed for*	*Type of source*			
	Accessibility	*Oversizing*	*Distribution*	*Controllability*	*Technical circularity*		*Paper*	*Other*	*Assessment tool*	*Case study*
Brand [20]	+	-	-	-	-	TS		Book		
Gann and Barlow [31]	-	-	-	+	-	TS	JP			
Geraedts [46]	+	+	+	+	+	TS & VS			✓	✓
Webb et al. [63]	-	-	-	-	+	TS	JP			
Keymer [68]	+	-/+	+	-/+	-	TS & VS		Thesis		✓
Slaughter [53]	-/+	-/+	-	-	-	TS	JP			
Durmisevic [25]	+	-	-	-	+	TS & VS		Thesis	✓	✓
Geraedts [33]	+	-/+	-/+	-/+	+	TS	CP			
Beadle et al. [67]	-	-	-	-	-/+	TS	CP			✓
Fuster et al. [48]	-/+	-	-/+	-	-/+	TS & VS	CP			✓
Nakib [47]	-/+	-/+	-/+	-	-/+	TS	CP			
Grinnell et al. [66]	-	-	-	-	-/+	TS	JP			
Zivkovic & Jovanovic [50]	-	-	-/+	-	-	TS	JP			
Gosling et al. [23]	-/+	-/+	-	-	-	TS	JP			
Geraedts et al. [14]	-/+	-	-	-/+	-/+	TS	CP		✓	✓
Mysen et al. [64]	-	-	+	-	+	VS		Tech. report		
Carlebur [69]	-	-/+	-	-/+	-/+	TS		Thesis	✓	
Sprengers [34]	+	-	+	-	-	TS & VS		Thesis	✓	
Geldermans [65]	-	-	-	-	+	TS	CP			
Heidrich et al. [18]	-/+	-	-/+	-	-/+	TS	RP			
Lützkendorf [62]	-	-	-	-	-/+	TS	JP			
Andrade and Bragana [70]	-/+	-	-	-	-/+	TS	CP		✓	
Cavalliere et al. [51]	-	-	+	-	-	TS	JP			
Scuderi [54]	-/+	-	-/+	-	-	TS	JP			
OVAM [52]	-/+	-/+	-	-/+	-/+	VS		Tech. report		

4. Ventilation strategies that allow for a flexible usage

Among the numerous strategies that can be adopted to ventilate a building, there are some strategies that already (partly) allow for a flexible usage. A selection was made of five ventilation strategies that included some of the adaptability characteristics that where discussed in the previous section. The first one concerns a centralized balanced mechanical ventilation system and will serve as the reference strategy in a flexible context while the other four are more innovative ventilation strategies. The main characteristics are described for each ventilation system. As there no case studies that have researched the sustainability of ventilation systems in an adaptable context, additional case studies are included that focus on the energy performance of these ventilation systems as a proxy indicator for sustainability. Finally, the adaptability characteristics of these five strategies will be assessed and the boundary conditions and to which extent they allow for a flexible usage will be compared. An overview of this is given in Table 2. The flexible usage for which these ventilation strategies allow will be divided into short term and long term flexibility. These kinds of flexible usage are again subdivided in building usage and the possibility to reconfigure the floorplan layout.

4.1. Centralized balanced mechanical ventilation

A suggested strategy by Netwerk Architecten Vlaanderen [55], is to use a centralized balanced mechanical ventilation system with oversized ductwork and ample inlets and outlets in a flexible context. Oversizing the hydraulic diameter of the ductwork and the maximum air flow of the fans can be seen as effective in terms of adaptability, since this anticipates on future scenarios where a higher ventilation rate might be required. Moreover, the great amount of inlets and outlets can make it possible to reconfigure the floorplan layout without having to adjust the air distribution network. The positions of these inlets and outlets should be based on multiple realistic configurations for a building, e.g. the classrooms of a school building can be configured in multiple ways. Finally, it is also possible to control this kind of ventilation system at the local level, which also enhances its adaptability. A disadvantage of this strategy is that it can also require a higher energy consumption by the fans as an extensive network of ductwork can cause more pressure drops [56]. Furthermore, because of the great amount of material that is required, this ventilation strategy has a high initial environmental and financial impact.

This strategy can allow for short term flexibility, mainly because it can be controlled at the local level and it has the capacity to deliver higher volume flow rates because of its oversized ductwork and fans with a high maximum air flow. Centralized balanced mechanical ventilation can also allow for long term flexibility, but there are some boundary conditions. An important factor for long term flexibility is that the components are accessible so that they can be easily maintained or replaced. Since this strategy contains a lot of ductwork, it is important that this ductwork is accessible. As stated by the layering model [20], the ductwork should not be integrated in the structural components. This can be solved by using a lowered ceiling. However, it is not possible to use a lowered ceiling in every building. It is stated by Remøy and van der Voordt [71] that the floor-to-floor height should be minimum about three meters to allow for mechanical ventilation above a lowered ceiling. When the floor slab is supported by beams, additional height is required since ductwork should not penetrate these beams. Moreover, the large amount of ductwork can also cause technical problems during other large refurbishments. When it comes to reconfiguring a building, this strategy is not optimal despite having multiple inlets and outlets. The great amount of ductwork is not compatible with the use of demountable and reusable walls. This can be partly solved by using a lowered ceiling, if the floor-to-floor height is adequate. However, this can also lead to acoustical leaks and problems regarding fire safety as illustrated in Figure 4.

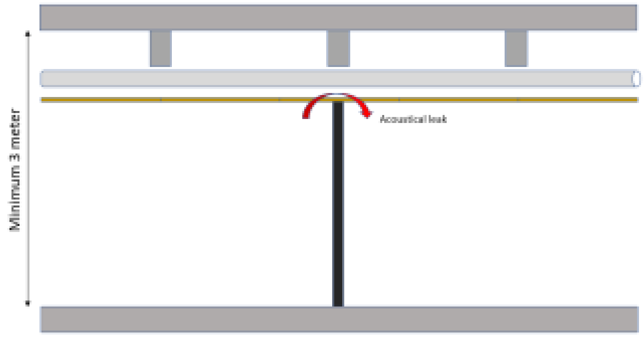


Figure 4. Using a lowered ceiling can cause acoustical leaks and requires a minimum floor-to-floor height

4.2. Mixed-mode ventilation

A more innovative ventilation strategy that can allow for a flexible usage, is mixed-mode ventilation. The principle behind mixed-mode ventilation relies on combining the advantages of both natural and mechanical driven ventilation while avoiding their disadvantages. When the natural conditions are favorable, the mixed-mode ventilation system will operate as a natural ventilation system. However, as natural ventilation cannot be controlled [72,73], the mixed-mode ventilation system will operate as a mechanical ventilation system when the natural forces are inadequate. So a mixed-mode ventilation system can be defined as a two-mode system which is controlled to maintain an acceptable indoor air quality and thermal comfort while minimizing the energy consumption [74]. In a study carried out by Homod and Sahari [75] on a residential building in a passive climate, it was found that more than 25% energy could be saved using a mixed-mode system instead of a solely mechanical ventilation system. Moreover, Ezzeldin and Rees [76] studied the potential of using mixed-mode ventilation in office buildings in an arid climate. They found that 40% energy can be saved compared to a fully mechanical ventilation system. It is even stated by Salcido et al. [77] that up to 75% energy can be saved in office buildings in hot climates when mixed-mode ventilation is applied properly. Generally mixed-mode ventilation can be categorized in three main principles, which are illustrated in Figure 5: natural and mechanical ventilation, fan-assisted natural ventilation and stack and wind-assisted mechanical ventilation [36,78].

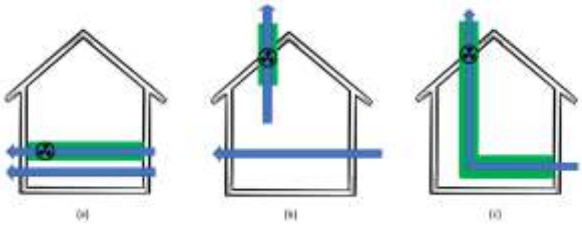


Figure 5. Overview of different mixed-mode ventilation principles. (a) Natural and mechanical ventilation; (b) Fan-assisted natural ventilation; (c) Stack and wind-assisted mechanical ventilation

Although this ventilation strategy is flexible in its operating modus, the goal of this strategy is rather to reduce the energy consumption than to allow for a flexible usage. However, mixed-mode ventilation strategies also have the potential to be adaptive [78]. This potential depends on how the mixed-mode ventilation system is designed. When the mixed-mode ventilation system solely alters its operating mode between a fully independent natural and mechanical ventilation system, its potential in terms of adaptability remains limited. Despite the fact that the building can be fully naturally ventilated, which does not require ductwork and thus increases the adaptability, a fully mechanical ventilation system is present as well. Although this mechanical ventilation system is not always in operating modus, it is still accompanied with the same problems as discussed for a centralized balanced mechanical ventilation system. Fan-assisted natural ventilation however, has almost no ductwork and thus has some opportunities regarding adaptability. Moreover, the absence of ductwork decreases the initial environmental and financial impact. However, there are also some disadvantages. First of all, it is not easy to apply heat recovery for this strategy. Secondly, it is very difficult to control this ventilation system at the local level. Therefore this kind of ventilation does not allow for a short term flexibility. Conversely, this ventilation system does allow for a long term flexibility as there is no ductwork that needs to be maintained or replaced nor can hinder other large refurbishments. Finally, this ventilation strategy is also compatible with demountable and reusable walls. As there is no ductwork present, many configurations can be applied without ductwork penetrating these walls causing technical problems. It has to be noted that the air flow pattern should be designed in such a way that it can facilitate multiple configurations, e.g. by providing ample vents.

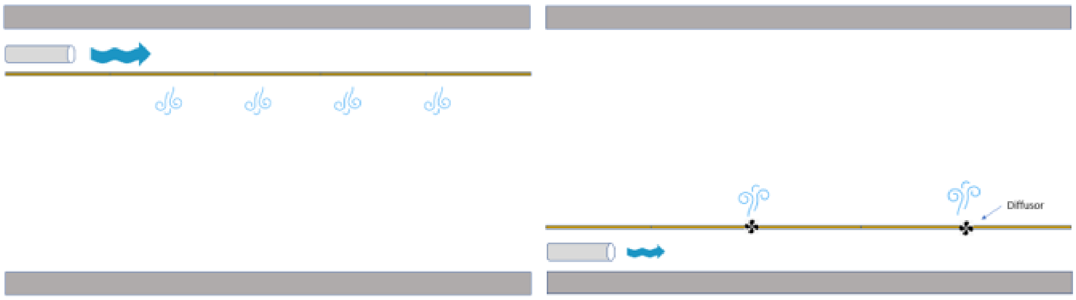
4.3. Low-pressure ventilation

Several components in a ventilation system, such as an extensive network of ductwork, coils, filters and heat exchangers, cause pressure drops. As the pressure difference increases, so does the required energy to obtain the targeted air flow rate. Currently mechanical ventilation systems are typically designed in commercial buildings for a total static pressure difference of approximately 800-1600 Pa [79]. The rationale behind low-pressure ventilation is to reduce the pressure drops, and thus the auxiliary energy consumption, as much as possible. Generally, low-pressure ventilation can be reached through three strategies: natural ventilation systems, mixed-mode ventilation systems and optimized mechanical ventilation. The first two have already been discussed.

There are several ways to design optimized mechanical ventilation systems. One method is to use a decentralized ventilation system, which is accompanied with fewer pressure drops compared to a centralized ventilation system because it uses less ductwork. Another method is to design every component of a traditional mechanical ventilation system in a proper way. It is stated by Schild [80] that a good design can increase the efficiency of the ventilation system by more than 20% compared to a bad design. For example, avoiding a lot of sharp bends in the ductwork can decrease the pressure drop. Since this is still a fully mechanical ventilation system, the problems regarding adaptability remain.

Another possibility is to adopt alternative mechanical ventilation systems. Using diffuse ceiling ventilation is an example of such an alternative system. The principle of diffuse ceiling ventilation is that fresh or conditioned air is supplied to the plenum and due to the pressure difference between the plenum and the room, the air is diffused through the perforated ceiling into the room [81,82]. Diffuse ceiling ventilation is characterized by a low energy consumption of fans without compromising thermal comfort or indoor air quality [83]. In an experimental study carried out in a climate chamber by Hviid and Svendsen [84] on two types of perforated dropped ceilings as diffuse ventilation inlet, it was found that the pressure drop of the diffuse ceiling ventilation was smaller than 2 Pa. As a result of this low pressure drop, a significant amount of fan energy can be saved by using diffuse ceiling ventilation. Jacobs and Knoll [85] researched the energy consumption in two Dutch school being ventilated through diffuse ceiling ventilation. While a traditional ventilation system uses 5-10 kWh/m³, it was found that the fans in the Dutch schools consumed only 0.04 and 0.5 kWh/m³. There are however some boundary conditions for this kind of ventilation. First of all, it is stated by Zhang et al. [86] that the height of the room should be lower than three meters to decrease draught risks, while the height of the plenum should be at least 10 cm to avoid large temperature variations. Moreover, if the size of the room is more than 150-200 m² or the maximum distance to the plenum inlet is more than 10 m, a very uneven air distribution of the air will occur, leading to problems both with thermal comfort and indoor air quality [86]. This can be solved by providing more inlets over the plenum, dividing the plenum over smaller sections or using a perforated duct to distribute air in the plenum.

Another alternative is to use under floor air distribution systems (UFAD). With a UFAD, the air is supplied in the plenum between the concrete slab and the raised floor and is brought into the room through diffusers which are mounted on the raised floor [87]. Although in some cases they are fixed, these diffusers are most commonly adjustable [37]. Moreover, it is stated by Bauman and Daly [88] and Ho et al. [89] that a UFAD system can lead to reduced life cycle costs and improved thermal comfort and indoor air quality. Due to their low pressure losses, UFAD also has the potential to reduce energy consumption. In a case study carried out by Alajmi and El-Amer [90], a conventional mechanical ventilation system and UFAD were compared in a commercial building in Kuwait. The findings have shown that 30% energy was saved using UFAD. A different study, carried out by Bauman et al. [91], compared two similarly designed office buildings located in California using measured data from these buildings. One of these buildings uses a conventional mechanical VAV ventilation system, while the other building uses UFAD. It was concluded that the annual cooling energy is 31% higher and the total annual fan energy is 50% higher for the conventional mechanical ventilation system compared to UFAD. Also for this kind of ventilation a greater amount of inlets is required when the area of the space increases. The principles of both diffuse ceiling ventilation and UFAD are illustrated in Figure 6.



(a)
(b)

Figure 6. (a) Diffuse ceiling ventilation; (b) Under floor air distribution

Both diffuse ceiling ventilation and UFAD have multiple benefits in terms of adaptability. Firstly, both strategies supply air through a plenum, which by design has a great capacity. Secondly, the ventilation systems are rather accessible. Moreover, the usage of a lowered ceiling or a raised floor also facilitates covering the distribution network of other technical services, such as data wiring or sanitary pipes. A disadvantage is that the use of such a lowered ceiling or raised floor can also result in acoustical leaks and issues regarding fire safety. Finally, both strategies can also be (partly) controlled at the local level. Because of this, diffuse ceiling ventilation and UFAD can allow for a short term flexible usage. Since both systems are easy accessible they also allow for a long term flexibility. However, as ductwork can still be necessary to distribute the air to the plenum, this can still hinder refurbishments. Finally, diffuse ceiling ventilation and UFAD also allow a room to be reconfigured as there is no ductwork present [68]. Especially diffuse ceiling ventilation facilitates the possibilities of a reconfiguration as it supplies air through the entire ceiling. Therefore, the possibilities of reconfiguring a floorplan layout are not constrained by the location of inlets and outlets. It should also be noted that these systems can be applied in buildings with a small floor-to-floor height, which is not the case for ventilation systems where voluminous ductwork is used. However it should be mentioned that the possibilities of diffuse ceiling ventilation and UFAD are not endless. When the floor-to-floor height is either too low or too high or when the area of the room becomes too large, it becomes difficult to apply either one of those systems without having to take measures that might decrease the adaptability.

4.4. Multi-mode ventilation

A third ventilation strategy, is multi-mode ventilation which is proposed by Shao et al. [92]. Multi-mode ventilation is a balanced mechanical ventilation system with multiple inlets and outlets in order to facilitate several air flow patterns. It is stated by Cheng et al. [93] and Heidarinejad et al. [94], that different air flow patterns can have a substantial influence on the energy consumption. Multi-mode ventilation anticipates on this. Based on which occupant or contaminant scenario is being detected, a certain air flow pattern will turn on while the others will be shut down. For example, there are two air flow patterns foreseen in the designed ventilation system (mode 1 and mode 2). Mode 1 is more effective to deal with contaminant scenario 1 and mode 2 is more effective to deal with contaminant scenario 2. So when an actual situation is detected that is closer to situation 1 than situation 2, the ventilation mode will be switched to ventilation mode 1, i.e. the dampers of mode 1 are turned on and the dampers of mode 2 are turned off. Conversely, when a situation is detected that is closer to situation 2, the ventilation mode will be switched to ventilation mode 2. A numerical study on a meeting room was carried by Shao et al. [92]. The results show that a reduction up to 56.8% in cooling load can be achieved using multi-mode ventilation rather than single-mode ventilation.

Although this kind of ventilation strategy responds to different flexibility scenarios, it rather increases the energy performances than the adaptability. It has the capability to respond to a short term flexibility, since it is controlled at the local level and responds to different scenarios. However, since it uses an extensive network of ductwork this may hinder long term flexibility and the reconfiguration of the floorplan layout. Moreover, this strategy has a large initial environmental and financial impact since it uses a great amount of ductwork and inlets and outlets to facilitate multiple air flow patterns.

4.5. Personalized ventilation

Finally, personalized ventilation will be discussed. Personalized ventilation aims to supply clean air directly to the breathing zone of the users [95]. So the rationale behind this strategy is to increase health and comfort for individual building occupants compared to other ventilation strategies [96]. Melikov et al. [97] stated that personalized ventilation can increase the ventilation effectiveness up to 20 times compared to other ventilation strategies. Also in terms of energy efficiency personalized ventilation has potential when applied properly. By carrying out simulations on an office building located in a hot and humid climate, Schiavon et al. [98] have found that personalized ventilation could reduce the energy consumption up to 51% compared to mechanical mixing ventilation if the right control strategies are applied. Other simulations have shown that office buildings that are located in a colder climate could reduce the energy consumption up to 60% when using the right control strategies [99]. Ductless personalized ventilation is a variant that combines the advantages of personalized ventilation with flexibility [100]. Fresh air is supplied under a raised floor and brought to the individual through a short duct system.

The benefit of ductless personalized ventilation in terms of adaptability is that this kind of ventilation makes it possible to relatively easily repartition the floorplan without compromising the air quality of the individuals. Yet the potential is rather limited. Personalized ventilation cannot respond to short term flexibility, since it can only be used in very static environments. When the function changes to something more dynamic, e.g. apartments or a shopping mall, a new kind of ventilation strategy is required. It does allow for longer term flexibility since ductless personalized ventilation is rather accessible and the raised floor can be used again to distribute air, but an adequate floor-to-floor height is required.

Table 2. Overview of the characteristics, boundary conditions and potential in terms of adaptability for different ventilation strategies. Legend for symbols and abbreviations: - = Bad; -/+ = Partly possible; + = Good; ✓ = Applicable; f-t-f height = Floor-to-floor height; Dec. possible = Decentralized possible

Ventilation characteristics	*Adaptive characteristics*	*Boundary conditions*	*Allows for*

	DCV	Fixed inlets	Ductwork	Dec. possible	Accessibility	Oversize	Distribution network	Controllability	Tech. Circularity	f-t-f height	Area	Function	Short term flexibility		Long term flexibility	
													Usage	Reconfiguration	Usage	Reconfiguration
Centralized balanced mechanical ventilation	✓	✓	✓	✓	-/+	+	-	+	+	✓			+	-	-/+	-
Mixed-mode ventilation (Fan assisted natural ventilation)		✓			+	-	+	-	+				-	+	+	+
Low-pressure ventilation (Diffuse ceiling ventilation & UFAD)	✓		✓	✓	+	+	+	-/+	+	✓	✓		-/+	+	-/+	+
Multi-mode ventilation	✓	✓	✓	✓	-/+	+	-	+	+	✓			+	-	-/+	-
Personalized ventilation	✓	✓			+	-/+	-	-/+	+	✓		✓	-	-/+	-/+	-/+

5. Discussion

In this discussion section, the research findings will be analyzed and discussed. Firstly, the proposed measures and guidelines will be reviewed. Secondly, the shortcomings and potential of the five discussed ventilation strategies will be discussed. Finally, based on the shortcomings of the current state-of-the-art, recommendations for further research will be proposed.

5.1. Measures and guidelines

Several guidelines have been proposed to improve the adaptability of ventilation systems. While some of these guidelines are clearly important, such as making sure that the ventilation system is accessible for maintenance, ensuring that the ventilation can be controlled at the local level and making the system demountable and using reusable and standardized components, other measures are somewhat contradictory. The oversizing of the distribution network is a good example of this. Providing extra capacity for future scenarios where a higher air flow rate is required, is surely favorable in terms of a short term flexible usage. However, oversized ductwork also has its limitations. Voluminous ductwork is not compatible with demountable and reusable walls that make it possible to reconfigure a room in a sustainable way. This can partly be solved by using a lowered ceiling, but this can still cause acoustical leaks and fire safety issues. Moreover, there are also some boundary conditions to applying oversized ductwork. Some structures are not compatible with the usage of voluminous ductwork, thus making it unfit for installation in all existing buildings. For example, a building where the floor-to-floor height is too low cannot facilitate the usage of a lowered ceiling to cover the ductwork. Moreover, because more raw materials are used, oversizing ductwork has a higher initial environmental and financial impact. It is also found by Khan et al. [101] that air handling units are often too oversized, with a higher energy consumption and environmental impact as a result.

Furthermore, as can be deducted from Table 1, most of the discussed guidelines and measures concern technical installations as a whole. Consequently, some measures lack an amount of detail [27]. A ventilation system cannot be entirely compared with heating systems, data wiring or sanitary facilities. For example, it is stated that the total absence of a physical distribution net is desirable. Regarding ventilation, this means that the supply and exhaust should be entirely natural. Since the natural forces that are the drivers of natural ventilation cannot be controlled, it is almost impossible to reach the strict minimum ventilation rates at all times. Therefore it would be desirable to provide more guidelines that are developed specifically for the distribution of a ventilation system. Besides guidelines and measures that are included in technical sheets and assessment tools, it is stated by

Heidrich et al. [18] and Phillips et al. [102] that it is important to develop concrete procedures that can be followed to increase the adaptability.

5.2. Adaptable ventilation strategies

As discussed in the previous section, there are already ventilation strategies that partly include measures that are proposed to improve the adaptability of ventilation systems. The traditional solution, i.e. a centralized balanced mechanical ventilation system with oversized ductwork and a great amount of inlets and outlets, has proven to have several limitations in terms of adaptability. Despite the fact that this strategy makes it possible to reconfigure the floorplan layout, the voluminous ductwork may also cause technical problems in a real and adaptable context where demountable and reusable walls are used. Secondly, the ductwork can be accessible when using a lowered ceiling, but if the floor-to-floor height is relatively low and if the floor slab is supported by beams, this becomes difficult. Furthermore, this kind of ventilation uses a great amount of raw materials compared to other ventilation strategies, resulting in a higher initial environmental and financial impact. Moreover, an extensive network of ductwork will create a lot of pressure drops with a great auxiliary energy consumption as a result.

Some of the discussed alternative ventilation strategies can partly overcome the shortcomings of the traditional solution, despite the fact that the rationale behind these strategies is to improve the indoor air quality and energy efficiency rather than to increase the adaptability. The most promising concepts are mixed-mode and low-pressure ventilation, although it strongly depends on how they are designed since this can be done in many ways. For mixed-mode ventilation systems, fan-assisted natural ventilation has a great potential since less ductwork is required. The main disadvantage of this strategy is that it is difficult to control the ventilation system at the local level with as a result that it does not allow for short term flexibility. For low-pressure ventilation systems, solutions such as a diffuse ceiling ventilation and under floor air distributions are interesting since they use a plenum instead of ductwork to deliver fresh or conditioned air to a room. Consequently, these strategies make it easy to reconfigure the floorplan layout. However, there are some boundary conditions to applying a diffuse ceiling ventilation or UFAD. These systems can only be adopted for rooms with a small area or other measures must be taken that might decrease the adaptability. Secondly, to apply a diffuse ceiling ventilation, the floor-to-floor height of the room should be lower than 3 m to decrease draught risks. That notwithstanding, this ventilation system can be applied in buildings with a lower floor-to-floor height, which is not the case for a ventilation system which uses a lowered ceiling to cover voluminous ductwork. This is a problem since it is stated that a room should be higher than 3 m to be adaptable, e.g. to serve for different functions in the future [46].

The potential of multi-mode and personal ventilation is limited in terms of adaptability. Multi-mode ventilation quite resembles a centralized balanced mechanical ventilation system with many inlets and outlets. The main difference is that multi-mode ventilation can alter between multiple air flow patterns based on which scenario occurs. However, the flexibility scenarios are rather limited. When it comes to personalized (ductless) ventilation, the goal is mainly to improve comfort and the health situation of individual building occupants and is only useful for very static environments.

The rationale behind all these strategies is not to become more adaptable. As shown in the overview in Table 2, all the discussed strategies have their limitations in terms of adaptability. Therefore, it would be interesting to invent or design more holistic ventilation strategies that ensure a good indoor air quality while also allowing for flexible usage. A recommendation would be to explore the possibilities of designing a ventilation strategy that uses less ductwork, can easily be controlled at the local level and which can be applied in a wide range of buildings and is not dependent on other building factors such as the floor-to-floor height. For example, the hollow space between demountable and reusable walls might be integrated in the ventilation design.

5.3. Further research

It is important to bear in mind that adaptability is only a tool, and not the goal. Although it seems promising, increasing the adaptability does not automatically lead to more sustainable buildings [103]. Therefore it is important that adaptable concepts are quantitively assessed [104,105]. Established methods for such assessments are life cycle assessment (LCA) and life cycle cost analysis (LCCA). These assessments can be carried out following the general framework provided by ISO 14044 for LCA and ISO 15686-5 for LCCA [106,107]. An example of how to carry out an LCA- and LCCA-study in a flexible context is the study carried out by Buyle et al. [103]. In this research, which is situated in a Belgian context, several internal walls are compared to each other over a period of 60 years with a reconfiguration of the floorplan layout every 15 years. It was found that demountable walls that could be reused had the potential to have a lower environmental and financial impact, given that their ability to be demounted and reused is exploited to its maximum. Other case studies conducted by Vandenbroucke et al. [108] and Brambilla et al. [109] also confirmed that reusable designs outperform conventional ones in terms of environmental impact. Concerning HVAC systems, Milwicz and Pasławski [110] compared the life cycle cost from several heating systems in a flexible context for a single family building. Similar case studies can be carried out where the environmental and financial impacts of different ventilation strategies can be compared to each other over an entire life cycle. Currently, there are only a few studies in the state-of-the-art that have carried out LCA- and LCCA-studies on ventilation systems, and they do not include flexible usage scenarios. For example, Fong et al. [111] found that stratum ventilation has the lowest environmental and financial impact over a period of 20 years in a school context, located in Hong Kong, compared to mixing and displacement ventilation. The results show that stratum ventilation, compared to mixing ventilation, reduces more than 30% of CO_2 emissions and 24% of the life cycle costs. In another case study carried out by Liu et al. [112], a chilled ceiling system was compared with a conventional VAV-system by means of an LCA-study over a period of 20 years. The case study concerned an office building located in Singapore. The results showed the chilled ceiling system had a lower environmental impact because of its great savings in terms of electricity consumption. Most other case studies only calculate the energy consumption of various ventilation systems as discussed in the previous section. Besides comparing ventilation strategies, a certain ventilation system can also be optimized based on these results. For example, it can be analyzed to which extent it is beneficial to oversize ventilation components.

These assessments are crucial to get a clearer view of the broader picture. Therefore it could be interesting to reevaluate the legal framework concerning ventilation systems and to include the results of the assessments of the environmental and financial impacts over the entire lifespan in the decision-making process. Currently, some regulations are so strict that in some cases they exclude ventilation strategies, while they may have a significantly lower environmental and financial impact. For example, if a certain ventilation system results in a few more violations concerning the indoor air quality (obviously within a certain range), but still has a much lower environmental and financial impact than other ventilation systems over its entire lifespan, it would be unfortunate to exclude this system from the start.

Finally, the author also encourages further research into the possibilities of making adaptable ventilation systems financially interesting for stakeholders. The reason for this is that it is possible that adaptable ventilation systems have a higher initial financial cost, although they may pay for themselves after a longer period of time [113]. New business and revenue models might make it possible to still invest in adaptable solutions, despite their larger initial financial cost. It is already stated that the shift towards the circular economy is associated with the need to implement innovative business models [114,115]. Unfortunately, these models are lacking in the industry [116]. Possible business models are renting, leasing or pay-per-use models.

6. Conclusion

To create a sustainably built environment, it is crucial that infrastructure is used more extensively and flexibly. To allow for such a usage, buildings must be adaptable to facilitate changes during their lifespan. Ventilation systems are crucial in this transition, as a flexible usage leads to fluctuating ventilation requirements. However, there is a knowledge gap about how to incorporate ventilation systems in adaptable buildings in a sustainable way. This review paper has identified several adaptability characteristics and linked them to existing ventilation strategies. The main characteristics are the accessibility of ventilation components, the oversizing of the capacity to distribute air, the absence of ductwork, the possibility to control the ventilation system at the local level and the technical circularity of the ventilation system. There is, however, a strong need for more measures and guidelines that specifically apply to ventilation systems.

Moreover, five ventilation strategies are qualified in terms of their ability to allow for a flexible usage. Centralized balanced mechanical ventilation and multi-mode ventilation can allow for a short term flexibility since both strategies can be easily controlled at the local level. These systems can also allow for a long term flexibility, if the ductwork is placed behind a lowered ceiling and not integrated in structural components. They do not easily allow for a reconfiguration of the floorplan layout because of their great amount of ductwork. Mixed-mode ventilation, i.e. fan assisted natural ventilation, does not easily allow for a short term flexibility since it is difficult to control this system at the local level. It does facilitate long term flexibility and a reconfiguration of the floorplan layout since it uses no or little ductwork. Diffuse ceiling ventilation and under floor air distribution on the other hand do simplify a reconfiguration because the air is distributed over a large area. These low pressure systems can also - to a certain extent - allow for short and long term flexibility. The main disadvantage of these systems is that they have several boundary conditions. Personalized ventilation - despite having some of the adaptability characteristics - does not have a great potential in terms of adaptability since it can only be used in very static environments.

More research is needed to quantify the advantages of adaptable ventilation systems. Therefore it is recommended that LCA- & LCCA-studies be carried out in order to measure the environmental and financial impacts of several ventilation systems over their entire life cycle. Exploring the possibilities of adopting new business and revenue models for innovative adaptable ventilation systems is also to be encouraged, as this can make it financially more interesting to invest in such systems.

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