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Review

Application of Mixed-Mode Ventilation to Enhance Indoor Air Quality and Energy Efficiency in School Buildings

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Abstract: Indoor air quality and energy efficiency are instrumental aspects of school facility design and construction, as they directly affect the physical well-being, comfort, and academic output of both pupils and staff. The challenge of balancing the need for adequate ventilation to enhance indoor air quality with the goal of reducing energy consumption has long been a topic of debate. The implementation of mixed-mode ventilation systems with automated controls presents a promising solution to address this issue. However, a comprehensive literature review on this subject is still missing. To address this gap, this review examines the potential application of mixed-mode ventilation systems as a solution to attaining improved energy savings without compromising indoor air quality and thermal comfort in educational environments. Mixed-mode ventilation systems, which combine natural ventilation and mechanical ventilation, provide the versatility to alternate between or merge both methods based on real-time indoor and outdoor environmental conditions. By analyzing empirical studies, case studies, and theoretical models, this review investigates the efficacy of mixed-mode ventilation systems in minimizing energy use and enhancing indoor air quality. Essential elements such as operable windows, sensors, and sophisticated control technologies are evaluated to illustrate how mixed-mode ventilation systems dynamically optimize ventilation to sustain comfortable and healthy indoor climates. This paper further addresses the challenges linked to the design and implementation of mixed-mode ventilation systems, including complexities in control and the necessity for climate-adaptive strategies. The findings suggest that mixed-mode ventilation systems can considerably lower heating, ventilation, and air conditioning energy usage, with energy savings ranging from 20% to 60% across various climate zones, while also enhancing indoor air quality with advanced control systems and data-driven control strategies. In conclusion, mixed-mode ventilation systems offer a promising approach for school buildings to achieve energy efficiency and effective ventilation without sacrificing indoor environment quality.

Keywords: indoor air quality; energy efficiency; mixed-mode ventilation; natural ventilation; mechanical ventilation; school building

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1. Introduction

Maintaining optimal indoor air quality (IAQ) is essential for good health and increases the productivity of students and general school staff [1]. The opposite of this can result in health-related issues such as respiratory infections, asthma, or allergies [2]. These health-related issues can impact academic performances and general school operations caused by regular absenteeism among students and general school staff [3,4]. Moreover, research has indicated that IAQ has a direct impact on cognitive abilities, including focus and the retention of information. Consequently, ensuring high IAQ is crucial not just for promoting well-being but also for fostering an ideal educational setting.

One cannot downplay the importance of reduced energy consumption in the management of educational facilities. Schools rank high when it comes to energy use in facilities, and Heating Ventilation and Air Conditioning (HVAC) systems are a major contributor to that [5]. Reduction in operational cost and a low environmental footprint are the main motivations for striving to attain net-zero energy consumption in educational facilities [6]. Implementing energy-efficient practices and technologies in schools can reduce energy consumption, resulting in significant energy cost savings. The saved funds can be channeled to improve educational programs and facility upgrades [7].

IAQ and energy efficiency represent two pivotal facets of school building management systems. Enhanced IAQ effectively correlates with higher energy consumption facilitated by MV systems installed within the premises [8]. The challenge of balancing the need for adequate ventilation to enhance IAQ with the goal of reducing energy consumption has long been a topic of debate, which has become especially prominent during the pandemic [9]. The implementation of mixed-mode ventilation (MMV) systems with automated controls tailored to different climatic conditions is a promising solution to tackle this challenge by enhancing IAQ and energy efficiency [10]. MMV integrates natural ventilation (NV) and mechanical ventilation (MV), thereby decreasing the reliance on energy-intensive components like fans, heaters, and air conditioners of the MV system, all while upholding satisfactory IAQ levels. This holistic approach capitalizes on the advantages of both ventilation techniques to cultivate healthier and more energy-efficient educational settings [11].

MMV systems, through their design, provide a more adaptable and flexible solution to the ventilation requirements of educational buildings [12]. The dynamic nature of these systems is crucial in educational settings such as classrooms and study areas within school buildings, owing to the fluctuations in occupancy levels, movements, and activities that impact the overall indoor environment [13]. When outdoor weather conditions are favorable, MMV is designed to introduce outdoor air through windows as an alternative to MV, thereby reducing the dependence on energy-intensive mechanical systems while simultaneously enhancing indoor comfort and air quality [14].

The MMV system offers a proactive method for ventilation adjustment by utilizing real-time data including temperature, carbon dioxide (CO_2), volatile organic compounds (VOC), humidity, and occupancy levels [15]. This results in improved IAQ and energy efficiency by optimizing the ventilation requirements in educational facilities [16,17]. In summary, this capability is achieved by integrating operable windows, fans, inlets, exhaust systems, sensors, heat recovery units, controls, and monitors [17,18].

The school environment is impactful on students, given the substantial amount of time they spend there in a day [4]. The average student spends about 30% of their life in school and 70% of that in the classroom. Failure to meet IAQ and thermal comfort standards can affect the productivity of students [1]. High CO_2 levels, a high concentration of dust, specifically particulate matters less than 2.5 μm in diameter, or volatile organic compounds can increase the risk of respiratory disorders [19]. Aso, allergens such as dust mites, mold spores, and pollen can trigger asthma and other respiratory diseases. CO_2 concentration is higher among other pollutants because classroom occupants emit it; an increase in occupancy level has the tendency to increase the possibility of CO_2 concentrations above 1000 ppm. The effect on students includes headaches and fatigue [19].

Even though research cannot prove the direct relation between bad IAQ and absenteeism among students, it is obvious that minors are more exposed to frequent health disorders because their bodies are still developing [20]. For instance, a field investigation conducted in California identified a statistically significant decrement of 1.6% in absenteeism due to illness for every additional liter per second per individual (L/s per person) of ventilation supplied within an observed range of 1–20 L/s per person [21]. Hence, there is an increase in absenteeism among students and even school staff, which compromises learning and academic activities because students fall behind in their studies, or school staff are not available to teach or run the school effectively [22].

A study by Shaughnessy et al., Kabirikopaei et al., and Tess M Stafford explore the effects of IAQ on the cognitive functioning of students, which affects their academic performance through standardized tests with variable ventilation rates and variable levels of classroom environment quality [4,20,23]. It was revealed that students' performances on standardized tests vary under different classroom environment conditions. In a two-year study of elementary classrooms having an air exchange rate exceeding 7.1 L per second for each individual, the scores for a standardized math test were higher compared to the previous year when the ventilation rate was found to be less than 4 L per second per individual. The study results recorded an increase in students' mean scores by 0.5% for every liter per second elevation in the rate of ventilation [24].

An increase in ventilation rate and general air circulation in the classroom helps reduce CO_2 and other particulate matter concentrations, therefore improving IAQ [25]. This reduces fatigue and increases student comfort and general cognitive function, hence ensuring an increase in student productivity and overall academic performance [20].

In reference to the U.S. state department of energy, HVAC systems of schools can contribute up to 50% of energy consumption, while the U.S. Energy information administration calculates it at approximately 39% [7]. This makes the system a major contributor to energy consumption in school buildings and responsible for heating, cooling, and ventilation in all the indoor spaces of schools [26]. However, the contribution of HVAC systems to overall energy consumption may vary as a result of some elements. Factors like climatic conditions determine the level of cooling or heating required to ensure students are comfortable [27]. Within this parameter, building design, air permeability, and the thermophysical characteristics of the building's envelope are pivotal in influencing the operational efficacy of the HVAC system. It appears that new and retrofit buildings have good insulation and minimal ventilation losses compared to older school buildings that lack renovation [28]. However, a study by Mohelníková et al. evaluating school buildings' energy performance shows that school building renovations can only be impactful when then heat insulation quality of the building's external walls coupled with solar shading are improved. This is because the indoor environment of classrooms can be positively affected by the size and positioning of windows, which increases the heat gained from the sun [6].

The type of ventilation systems used by schools also contribute to overall energy efficiency. Schools in temperate and mild–temperate climatic areas rely more on NV during a major part of the year, which is a cheaper alternative and even more efficient when automated to adapt to the ventilation demand [21,29]. Schools in continental and tropical climatic areas rely on MV for heating and cooling during very cold winters and hot summers [30,31]. MV is less energy efficient but can meet the high ventilation demand [29]. Mixed-mode ventilation offers a better alternative for both tropical and temperate climatic areas if optimized for good IAQ and energy efficiency.

The frequency of maintenance of HVAC systems also contributes to their levels of efficiency. Studies show that well-maintained HVAC systems are more efficient in terms of IAQ and energy consumption [32]. HVAC systems require inspection and tuning twice a year before summer and winter. The least-maintained HVAC system loses 5% of its efficiency each year and needs to work overtime to supply the same level of heating and cooling, thus increasing energy consumption [33].

Also, HVAC system control in mechanical and mixed-mode ventilation is a contributing factor to the system's energy efficiency [34]. Manual control of natural, mechanical, or mixed-mode ventilation by occupants has the potential to elapse certain ventilation modes, even though it may provide the required thermal comfort, but does not enhance the overall indoor environment standard and energy savings due to the personal preferences of the occupants [29,35]. HVAC systems with automatic control algorithms designed to adapt to indoor environment conditions like occupancy levels, temperature, CO_2 concentration, and humidity prove to be more energy efficient and prove to have better IAQ [36].

While extensive research has investigated individual strategies for enhancing IAQ and energy efficiency in educational facilities, a thorough review of how MMV systems can effectively tackle both issues simultaneously is still missing. Existing research has mainly concentrated on either the separate application of MV or NV in schools or the application of MMV in residential or commercial buildings, overlooking the possible advantages of combining both methods in practical educational settings. Peng et al. [37] conducted a review on NV and MV controls in MMV buildings; the study took a broader scope without being specific to school buildings. Peng et al. [38] also conducted a review on low-energy ventilation strategies in the cold regions of China, limiting the study to a single climate. A review on MMV as a comfortable low-energy solution by Kim et al. [12] touched on thermal comfort and not the overall IAQ of a ventilated space, and Jia et al. [2] conducted a review on the interaction between thermal comfort IAQ and energy consumption of educational buildings, exploring NV and MV, but had a limited overview of MMV and its application in educational buildings.

To address this gap, this present study conducts an in-depth literature review focused on assessing MMV systems' effectiveness in improving IAQ and reducing energy consumption in the context of educational facilities across various contexts, including different building types, climate conditions, and operational strategies. This was achieved through an extensive review of various sources to present a comprehensive examination of MMV systems in educational facilities. This included a variety of literature types, such as empirical research, theoretical discussions, and practical case studies. This adaptability proved advantageous when delving into intricate and interdisciplinary subjects like MMV systems, which involve elements of engineering, environmental science, and facility administration.

This review aims to explore the effectiveness of MMV systems and identify key control strategies, technologies, and system configurations for implementation in school buildings. It will analyze components like natural and MV types, sensors, controls, and the role of advanced technologies like artificial intelligence. Understanding these elements is crucial for designing and implementing adaptive MMV systems in school environments. The structure of this review is illustrated by Figure 1.

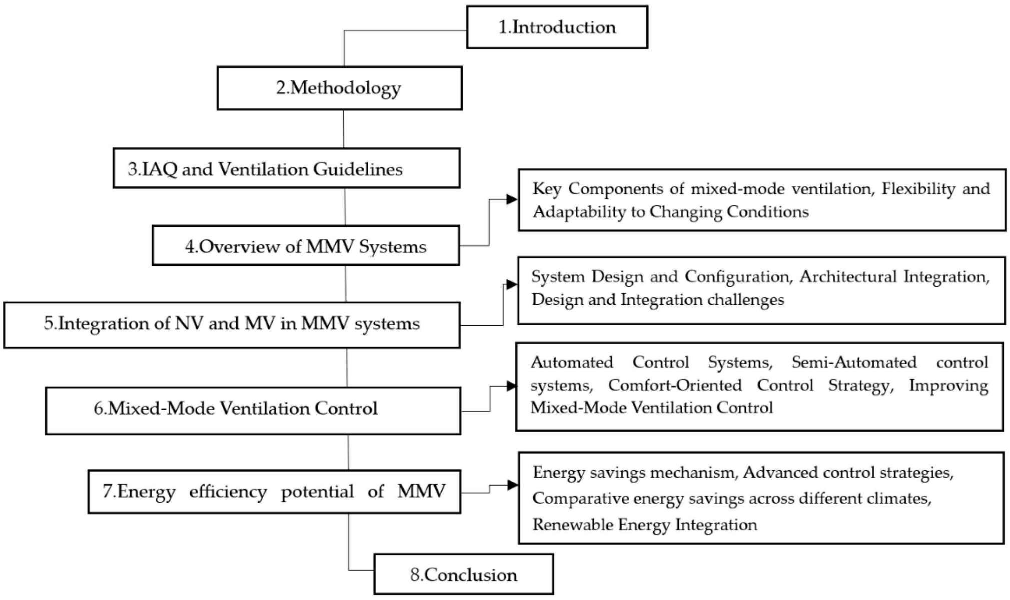

Figure 1. Structure of this study.

2. Methodology

This review adhered to a methodical procedure, commencing with the identification of pertinent studies in the literature through extensive searches of Science Direct, Scopus, and Google Scholar databases. The search was conducted with the keywords Mixed-mode ventilation, Indoor Air Quality, Energy efficiency, and School building. A wide range of studies were collected and narrowed down to those that were the most insightful and relevant to this review.

The literature selection process for this review adhered to particular inclusion and exclusion criteria to ascertain the pertinence and caliber of the sources. The inclusion criteria, as shown by Table 1, were centered on studies and articles presenting empirical data on MMV systems' performance, detailed descriptions of MMV components and strategies, and comprehensive reviews of IAQ and energy efficiency outcomes. Sources were chosen from peer-reviewed journals, industry reports, and reputable organizations to guarantee the information's reliability and validity. Exclusion criteria were applied to filter out the literature lacking robust methodology, being outdated, or not directly addressing the review's key themes and this is shown by Figure 2 [39].

Table 1. Inclusion and exclusion criteria of articles for this study.

Criteria	Description
Topic	Articles must contain the key words Mixed-Mode Ventilation, Indoor Air Quality, Energy Efficiency, and School Buildings either in the title or abstract.
Year of Publication	Only articles published in the last 20 years. (80% of articles were published in the last 5 years.)
Publication Status	Only peer-reviewed journal articles.
Study Design	Empirical (both qualitative and quantitative methods).

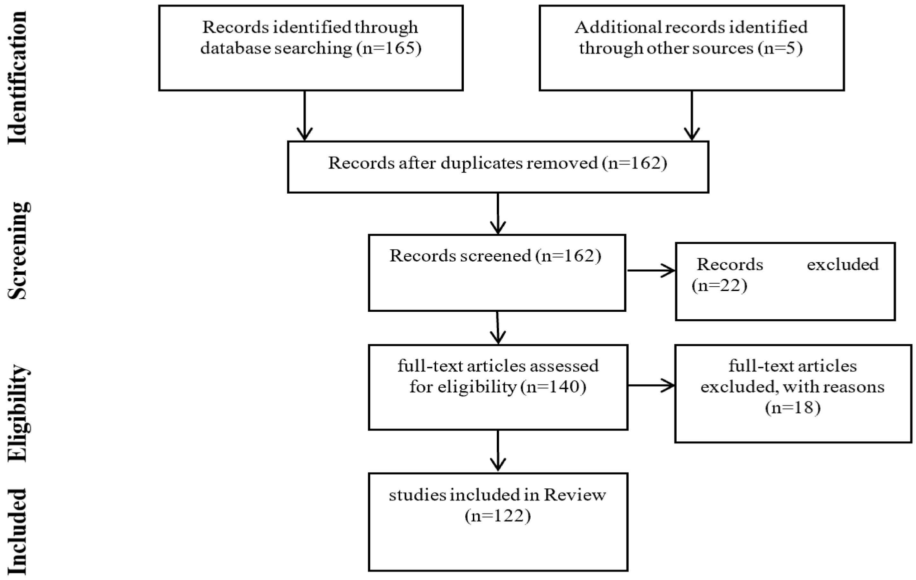

Figure 2. Flow chart of the study screening process.

The examination of the chosen literature entailed a thorough scrutiny of the methodologies, findings, and conclusions of each source. Essential data points, such as IAQ metrics, energy consumption statistics, and cost analyses, were extracted and compared across studies to detect patterns and trends. Furthermore, qualitative insights like expert opinions and case study narratives were amalgamated to offer a comprehensive perspective of MMV systems. The primary aim of this analytical procedure is to draw meaningful conclusions and practical recommendations to steer the optimal deployment of MMV systems in educational facilities.

3. Indoor Air Quality (IAQ) and Ventilation Guidelines

IAQ is an essential element that influences the health, productivity, and overall well-being of both students and staff within educational institutions. Significant pollutants impacting IAQ in schools encompass particulate matter (PM), carbon dioxide (CO_2), nitrogen dioxide (NO_2), volatile organic compounds (VOCs), carbon monoxide (CO), and biological contaminants, such as mold. Each of these pollutants poses unique health risks to children. These contaminants may arise from the external environment, particularly when natural ventilation (NV) is employed, or may be produced internally by occupants or building materials [40]. For example, particulate matter, especially PM2.5, is known to provoke asthma and other respiratory complications, while prolonged exposure to NO_2 can exacerbate asthma and diminish lung function. VOCs, which are released from building materials, furniture, and cleaning agents, are associated with respiratory irritation and cognitive difficulties, particularly in educational settings where children are in close contact with sources of these pollutants [41].

Ventilation is vital in alleviating the detrimental effects of these contaminants. Adequate ventilation facilitates the ongoing exchange of indoor air with outdoor air, thereby diluting indoor pollutants and contributing to thermal comfort. Conversely, insufficient ventilation results in the accumulation of pollutants, heightening the risk of negative health consequences [42]. In numerous schools, classrooms frequently experience overcrowding, leading to a swift increase in CO_2 and VOCs, particularly when ventilation systems are outdated or inadequate. This situation is especially concerning since CO_2 levels are commonly used as a measure of ventilation effectiveness in indoor environments. Elevated CO_2 levels, particularly those exceeding 1000 parts per million (ppm), have been linked to diminished concentration and cognitive performance, which directly affect students' educational achievements [43].

In light of these issues, a variety of guidelines and standards have been put in place to govern IAQ in educational institutions. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) offers Standard 62.1, which delineates the minimum ventilation standards required to ensure acceptable air quality in commercial and institutional buildings, including schools [44,45]. This standard recommends specific ventilation rates based on occupancy and building function, thereby ensuring that students and staff are subjected to safe concentrations of indoor pollutants. For instance, it advocates for outdoor air ventilation rates of 5–10 L per second per person for standard office environments, which corresponds to similar requirements for educational facilities [43]. However, despite these recommendations, many schools continue to face challenges in achieving the suggested ventilation rates due to aging infrastructure and financial limitations.

Global organizations, such as the World Health Organization (WHO), have also issued guidelines for upholding good IAQ in schools. The WHO's recommendations establish target limits for crucial pollutants, including PM2.5 (10 $\mu g/m^3$ annual mean; 25 $\mu g/m^3$ 24 h mean) and CO_2 (aiming for levels below 1000 ppm), and highlight the necessity of regular monitoring to guarantee that schools maintain safe air quality standards [40]. These guidelines are particularly vital in regions with elevated outdoor pollution, where schools may need additional filtration systems to block outdoor pollutants from entering indoor areas [46]. The WHO further underscores that effective ventilation practices are essential to dilute indoor pollutants and enhance overall air quality.

4. Overview of Mixed-Mode Ventilation (MMV) Systems

MMV systems integrate the benefits of NV and MV as a means to enhance IAQ and energy efficiency. The core concept of MMV involves capitalizing on the benefits of both NV and MV through dynamic switching between the two modes or their simultaneous operation, depending on environmental conditions and IAQ needs [12]. This combined strategy offers increased flexibility and adaptability for maintaining a pleasant and healthful indoor environment while reducing energy usage [14]. MMV systems prove to be particularly advantageous in regions with mild climates, where NV can be optimized in less extreme seasons and MV can be used as a supplement during harsh weather conditions [12,26].

NV is dependent on passive airflow induced by natural elements like wind and thermal buoyancy. It entails utilizing operable windows, vents, and other apertures to facilitate the exchange of indoor and outdoor air. Consequently, its efficacy is affected by conditions ranging from window dimensions and placement, architectural design and orientation, and the effectiveness of automated window control systems [47]. NV can prove to be remarkably effective in preserving IAQ under moderate weather conditions, thereby diminishing the necessity for energy-intensive mechanical systems [30]. Nonetheless, in extreme climates or densely populated areas where high IAQ standards are imperative, ventilation rates that exceed the capacity of NV become essential [16,26]. Figure 3 shows the cross, stack and single sided NV.

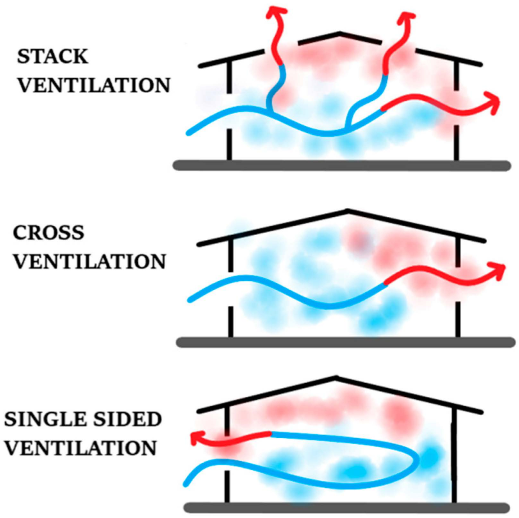

Figure 3. The concept of natural ventilation.

MV, as shown in Figure 4, conversely employs fans, ducts, and various mechanical elements for the purpose of offering regulated and uniform air circulation [48]. Ventilation systems utilizing mechanical means are imperative for upholding IAQ within structures where NV is insufficient, particularly in instances of severe climatic conditions or regions characterized by elevated levels of air pollution [3].

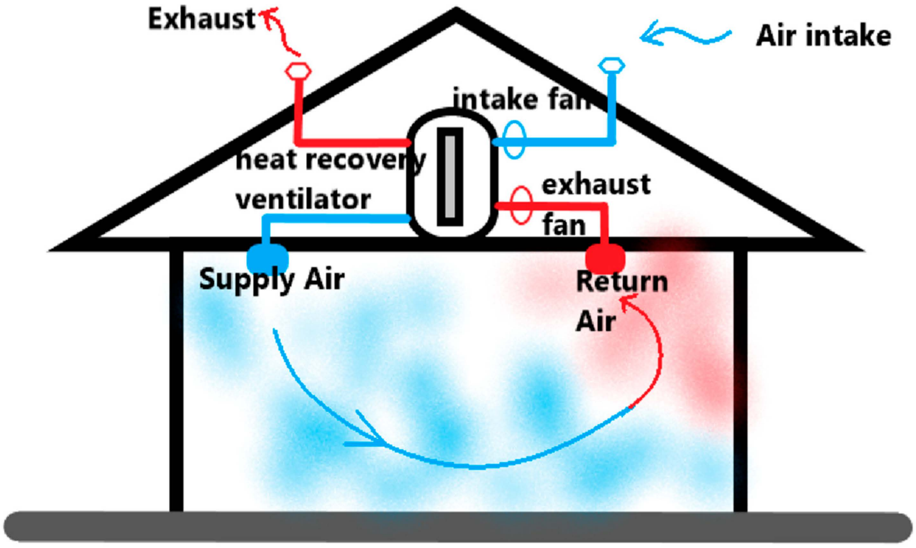

Figure 4. An example of mechanical ventilation.

4.1. Key Component of MMV System

The essential elements of MMV systems consist of operable windows, vents, HVAC systems, sensors, and advanced control technologies [49]. Each of these constituents assumes a crucial role in ensuring the efficient functionality of MMV systems and attaining the intended equilibrium between NV and MV [12]. The majority of MMV systems installed in commercial and educational facilities include variable air volume (VAV) terminal devices along with an air-handling unit (AHU), which constitutes the MV system, complemented by automatic controlled windows for the provision of NV [36].

Operable windows and vents play a vital role in the potency of NV within MMV systems [50]. Actuators control the windows, allowing for variable openings based on commands from the overall MMV system [29]. This facilitates passive indoor–outdoor air exchange driven by natural forces like wind pressure and thermal buoyancy [28]. Well-designed windows and strategically positioned vents can improve cross-ventilation and stack ventilation, ultimately enhancing IAQ and decreasing reliance on mechanical systems in favorable weather conditions [14].

HVAC systems, made up of air intake, air conditioning, and heat recovery units, are integral to the MV component of MMV systems [49]. These systems deliver regulated air supply and thermal balance for consistent IAQ and thermal comfort, irrespective of external circumstances [3]. Contemporary HVAC systems feature variable speed drives and sophisticated control algorithms, enabling the precise regulation of airflow and temperature, thus contributing to energy efficiency [16].

Sensors and controls serve as the technological foundation of MMV systems. Sensors oversee various internal and external environmental conditions such as temperature, humidity, CO_2 levels, and particulate matter [18]. Control systems utilize these real-time data to adapt ventilation strategies dynamically, transitioning between natural and mechanical modes or employing both concurrently to uphold optimal conditions [51]. Advanced control systems may integrate machine learning algorithms to anticipate ventilation requirements based on historical data and occupancy trends, thereby further augmenting the efficiency and efficacy of MMV systems [17]. The advancement of such intelligent systems is paramount in maximizing energy conservation while ensuring occupant well-being [52].

4.2. Flexibility and Adaptability to Changing Conditions

Another significant benefit of MMV systems is their intrinsic flexibility and adaptability to fluctuating indoor environmental and occupancy conditions [53]. The system is also capable of responding to external and climatic factors, and in contrast to conventional ventilation systems that depend exclusively on either natural or mechanical means, MMV systems can dynamically integrate and adjust their operations to align with real-time conditions, thereby ensuring optimal IAQ and thermal comfort consistently [14,54].

MMV can also offer a degree of adaptiveness, just like variable air volume MV, which is crucial in educational institutions where patterns of occupancy, student activities, and requirements for ventilation can fluctuate markedly throughout the day [49]. For instance, classrooms may experience high occupancy during instructional periods necessitating elevated ventilation rates, whereas other sections of the facility may exhibit reduced occupancy levels and distinct ventilation requirements [48,55]. MMV systems have the capability to adapt to these fluctuations by modifying ventilation approaches in response to sensor inputs, thereby ensuring that all spaces uphold satisfactory IAQ and thermal comfort standards [16,26].

The adaptability of MMV systems renders them particularly advantageous for a variety of climatic conditions [56]. In areas characterized by temperate climates, NV can be employed for a substantial portion of the year, thereby markedly diminishing the reliance on MV and its concomitant energy consumption [57]. In regions experiencing more extreme climatic conditions, MMV systems can effortlessly transition to MV to sustain IAQ and occupant comfort when NV proves inadequate. This capacity for adjustment across a broad spectrum of conditions establishes MMV systems as a multifaceted strategy for improving IAQ and energy efficiency in heterogeneous settings [17,26].

5. Integration of Natural Ventilation (NV) and Mechanical Ventilation (MV) in (MMV) Systems

The combination of the strengths found in both MV and NV systems, along with their respective strategies, results in a more efficient and versatile solution that cannot be achieved by either system on its own. To meet the stringent indoor environmental standards required for educational facilities, these systems should be carefully designed to address the unique needs of the academic institution based on prior studies and empirical evidence [58]. This strategy enhances system performance to achieve greater energy efficiency, improved IAQ, and heightened occupant comfort [48]. A combination of these systems allows for flexible transitions between NV and MV in response to seasonal and daily changes, thereby leveraging the advantages of both NV and MV for optimal operational performance throughout the year. MMV mitigates the shortcomings of both NV and MV systems while incorporating their benefits.

5.1. System Design and Configuration

MMV can be conceptualized to integrate MV and NV across three distinct system configurations, tailored to the requirements of educational edifices comprising various rooms designated for diverse activities [59,60]. Classrooms, administrative offices, laboratories, lobbies, and kitchen and dining spaces within an educational facility stand to gain from this adaptable configuration to satisfy optimal indoor environmental criteria [58].

- Concurrent ventilation facilitates the simultaneous employment of MV and NV within a shared space [61]. Environments characterized by fluctuating occupancy levels, devoid of specific temporal constraints, can benefit from the concurrent implementation of both ventilation methodologies, thereby ensuring a comfortable and hygienic indoor atmosphere [62]. This ventilation paradigm exhibits energy efficiency and possesses the capability to uphold commendable and stable IAQ [50]. The NV mode predominates, with the MV mode activating to augment the NV when IAQ, thermal comfort, or ventilation rates dip below established thresholds, or when external climatic conditions or air quality are deemed unsatisfactory [3]. The realization of this system design necessitates sophisticated control strategies and sensor technologies to yield optimal outcomes.
- Change-over ventilation allows for the sequential use of MV and NV modes within the same environment, albeit at varying times, days, or seasons, contingent upon both internal and external environmental parameters [61,63]. Informed by empirical data, the system can be programmed to switch between either ventilation modes at a variable time throughout the day [64]. Research indicates scenarios wherein NV is employed during the early hours in hot or warm climates, where minimal cooling is necessitated, and during midday in temperate or cold climates, where minimal heating is warranted [65]. Within academic institutions, NV modes can be employed on days characterized by reduced occupancy levels, requiring minimal ventilation rates [29]. In regions with extreme climatic conditions, this configuration can be adjusted seasonally, permitting the use of NV during milder climatic periods [56,66].
- Zoning ventilation facilitates the concurrent utilization of NV and MV across various segments of the educational building [61]. This arrangement can be particularly advantageous for schools wherein communal areas such as lobbies and recreational zones may depend on NV, while critical zones, including classrooms, server rooms, laboratories, and dining areas, may rely on MV [67].

MMV possesses the capability to offer a substantial degree of adaptability in its implementation [49]. There exist numerous methodologies for amalgamating NV and MV systems to achieve the desired ventilation outcomes as highlighted by Figure 5. Within the framework of concurrent optimization, wherein NV and MV functions concurrently as graphically illustrated by Figure 6, NV may facilitate incoming outdoor air, whereas mechanical systems are tasked with ensuring sufficient circulation and distribution to augment the comfort of the indoor environment [68]. This scenario is particularly pertinent in instances where the arrangement of NV windows and vents hampers effective air circulation within the designated space [69]. The advantage of this configuration lies in its allowance for both retrofitted structures and original edifices with insufficient window dimensions or placements to utilize MMV [70]. To attain the IAQ standards and thermal comfort in climates where educational institutions already depend on NV, MV may be incorporated to enable transitions between both modes in accordance with predetermined criteria [47]. For instance, NV may serve as the primary mode, with mechanical systems activated solely when NV fails to maintain established IAQ and thermal comfort thresholds [71].

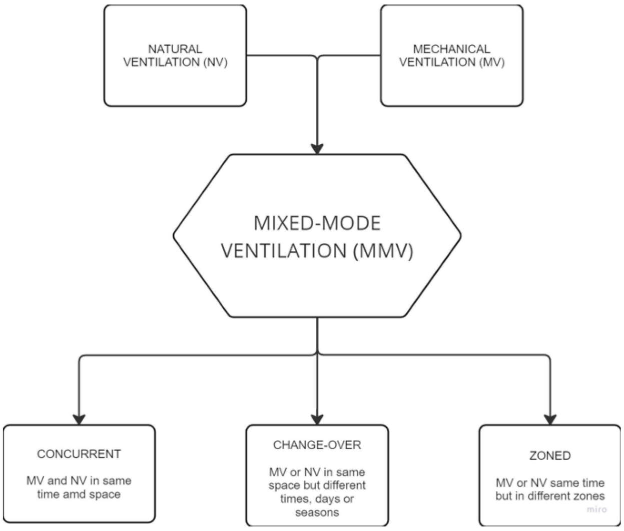

Figure 5. Mixed-mode design configuration.

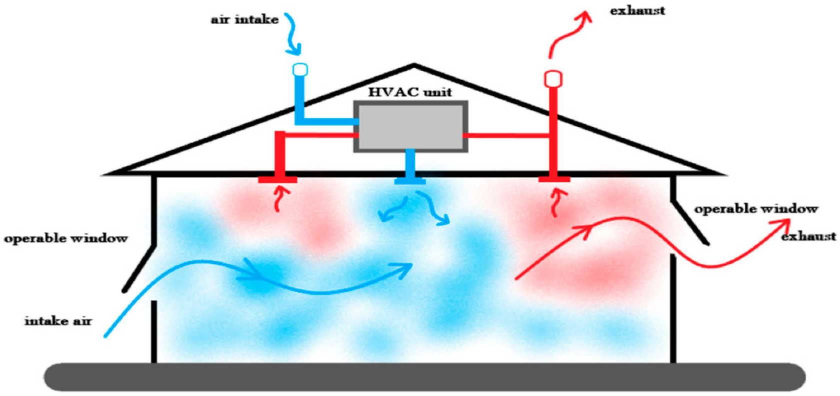

Figure 6. Concurrent mixed-mode ventilation design.

Heat Recovery Ventilators (HRVs) together with Energy Recovery Ventilators (ERVs) may be seamlessly incorporated into the MV framework for exhaust air heat recovery and preprocess incoming airflow, thereby enhancing MV system efficiency [5,72]. The optimization of thermal mass utilization during periods of NV is relevant in specific contexts, as thermal mass can function to retain coolness or warmth, which can subsequently be released when MV is operational, thereby contributing to a reduction in energy consumption [37].

5.2. Architectural Integration

In order to ensure the optimal functionality of MV systems within newly constructed educational facilities, it is imperative that the system's design be integrated into the architectural blueprint of the structure during the preliminary phases, thereby facilitating a cohesive blend of the ventilation apparatus with the facility's overall design and intended use [73]. This strategic approach mitigates the obstacles encountered during the ventilation system installation process and simultaneously enhances overall efficiency of the system [74]. Numerous elements must be addressed during the design and planning phase of a school facility intended to be equipped with MMV system [75]. A pivotal consideration is the building structure orientation, as it significantly influences the effectiveness of NV.

Strategically positioning of the building to harness prevailing winds will facilitate the alignment of vents and openings with predictable wind patterns, thereby optimizing the viability of the NV mode of the system [13].

The design and placement of windows are also critical in promoting natural airflow throughout the ventilated area. Such windows must be operable and judiciously located to encourage cross-ventilation [76]. Furthermore, features such as high-level vents can augment the stack effect, allowing for the expulsion of rising warm air while operable windows facilitate the influx of cooler air [62]. The design of the building's façade is equally vital, as it permits the incorporation of window-shading devices without compromising the aesthetic integrity of the structure [58]. Window shading serves to mitigate overheating while simultaneously allowing the windows to be opened for the intake of outdoor air.

5.3. Design and Integration Challenges

The balance between NV and MV poses a considerable challenge in the design and implementation of MMV systems. Educational facilities feature a variety of designs and spatial arrangements, while the existing climatic conditions also show significant variability [39]. As a result, no universal methodology exists that is applicable to the process of designing an MMV system that can cater to every function and application. To attain an ideal equilibrium in the system's design, it is essential to consider factors that are unique to the building, in addition to its internal and external environmental contexts [17].

A major hurdle in the design and implementation of MMV systems stems from the complexity of control systems [17]. The system's operational efficiency is heavily impacted by the control strategy and the algorithms that are utilized [29]. Due to the lack of standardized control algorithms in the field, it is crucial for each system to be outfitted with a custom control algorithm that can predict variations in both internal and external environmental conditions to trigger real-time adjustments to enable optimal IAQ and energy efficiency [74,75]. The complexity of these control systems significantly contributes to the expenses related to design, installation, and upkeep. Moreover, it requires specialized knowledge in system design, controls, and programming [25].

The compatibility of building design can also be a challenge when it comes to the design and implementation of MMV systems [76]. Some educational buildings are primarily designed to utilize NV, based on their locations and local climate. In these cases, the integration of mechanical systems must be carried out in a way that preserves the natural airflow and the aesthetic appeal of the building [77]. Furthermore, certain educational facilities are specifically constructed for MV, making retrofitting efforts to include NV more complicated due to inadequate window design and placement [38].

6. Mixed-Mode Ventilation (MMV) Control

Optimizing heating and cooling to attain and maintain the right thermohydrometric conditions in building spaces has significance for energy use [68]. Many studies have explored ways to improve an MMV system's energy consumption while maintaining the optimal IAQ [49]. Aside from building design improvements, advanced controls' integration in a building energy management system is a major element for achieving the maximum efficiency of the ventilation system. Recent years have seen an improvement in sensor technology, artificial intelligence, and advanced computational power, making it possible to develop highly efficient control architecture to attain this goal [78]. The challenge revolves around how to effectively combine and coordinate the operability of NV windows, vents, and openings with a mechanical air conditioning system [38]. The desired level of energy savings can only be attained in MMV school facilities when the control architecture succeeds in establishing the opening and closing periods of windows in a timely manner to respond to variations in internal and external environmental conditions. The difficulty lies in establishing the conditions that trigger the switch [79].

Advanced controls are based on a set strategy involving ventilation configuration, indoor environment comfort levels, and air quality standards [80]. It is important to develop a baseline control algorithm based on rules from the specification of the school building [63]. An advanced adaptive control algorithm can be compared to baseline control, and the former must outperform the latter to qualify for adoption. Obtaining the NV operating range is essential in building the adaptive control algorithm and is dependent on thermal comfort setpoints and air quality standard thresholds [50]. This operating range can be divided into sub-ranges, tested and analyzed to determine the best NV operating range based on the climate where the building is located in deferent seasons [63]. The NV operating ranges with the longest hot and cold hours that produce discomfort in the different seasons across a year can be determined, and the range with the highest energy saving and ventilation rate can be selected and integrated into the control algorithm [81].

Most MV controls rely on Predictive Mean Vote (PMV) models as per ASHRAE standard 55 to assess indoor comfort [44]. Research has evaluated the effectiveness of an adaptive controls model that incorporates PMV. This control model can serve as a foundation for enhancements aimed at achieving optimal energy efficiency while ensuring a conducive indoor environment in educational facilities [76]. An effectively synchronized control system guarantees that NV and MV operate in harmony to avoid scenarios where MV counteract NV by providing heat while windows are open to allow in cool, outdoor air [80]. Figure 7 shows a basic illustration of an MMV control model with integrated operable windows and vents, HVAC system, and indoor and outdoor sensors.

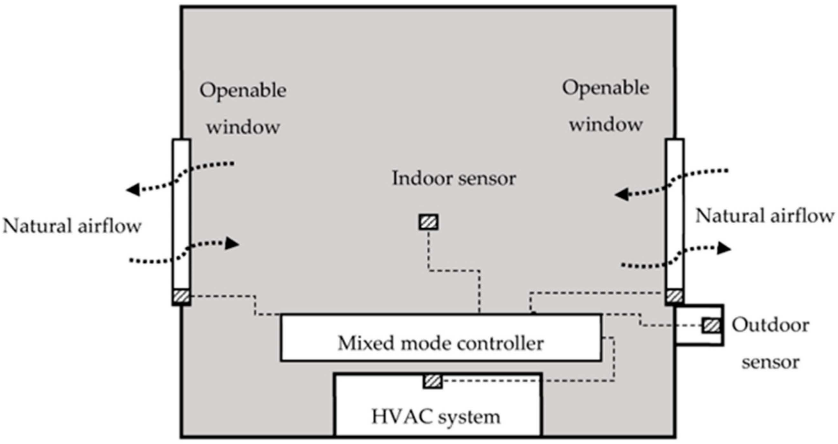

Figure 7. Basic mixed-mode ventilation control [49].

6.1. Automated Control Systems

Automated control in an MM-ventilated school building is a smart control system that handles window operation and the HVAC system by integrating it with a building automation system (BAS) [82]. The system operates on a predefined algorithm and parameters to maintain the indoor environment at a preset standard at every point in time [83]. Automated control utilizes smart sensors and, in recent times, artificial intelligence to analyze climate conditions and anticipate changes in outdoor environment conditions [35]. The system is also capable of predicting user preference and adjusting incoming air volumes to meet occupancy variations [84]. Despite the propensity for occupants to experience diminished control and adaptive possibilities within these edifices, such structures are deemed appropriate for educational facilities, as students may exhibit diverse thermal comfort preferences; furthermore, instructing all occupants on the operational mechanisms of ventilation systems could prove to be a significant undertaking, if not entirely unfeasible for younger individuals [27].

By contrast, automated MMV controls can potentially improve IAQ and the thermal comfort of occupants [85]. The system also ensures smooth transitions between NV and MV modes in concurrent ventilation and smooth response to changes in temperature requirement without occupants noticing. It also ensures good air circulation in the building envelope to prevent any discomfort caused by stale air to maintain a conducive learning environment. Automated MMV controls can provide very high energy efficiency and IAQ [86].

A research investigation undertaken by Khatami et al. [29] deduced that the implementation of automatic control systems markedly contributed to the mitigation of risks associated with inadequate IAQ. The incorporation of automated NV controls within the framework of MMV resulted in an 85% reduction in the duration during which CO_2 concentrations exceeded 1200 ppm. When juxtaposed with manual control mechanisms, automatic controls facilitated superior IAQ conditions; the findings of this research indicated that the deployment of automated control in MMV contributed to an 8% decrease in energy consumption. Nonetheless, the efficacy of this outcome is contingent upon the performance and adaptability of the control algorithm. With a feedback mechanism to provide channels for occupants to give feedback on comfort levels, the system can continuously be improved to be more efficient [29]. Figure 8 shows an advanced automated control architecture.

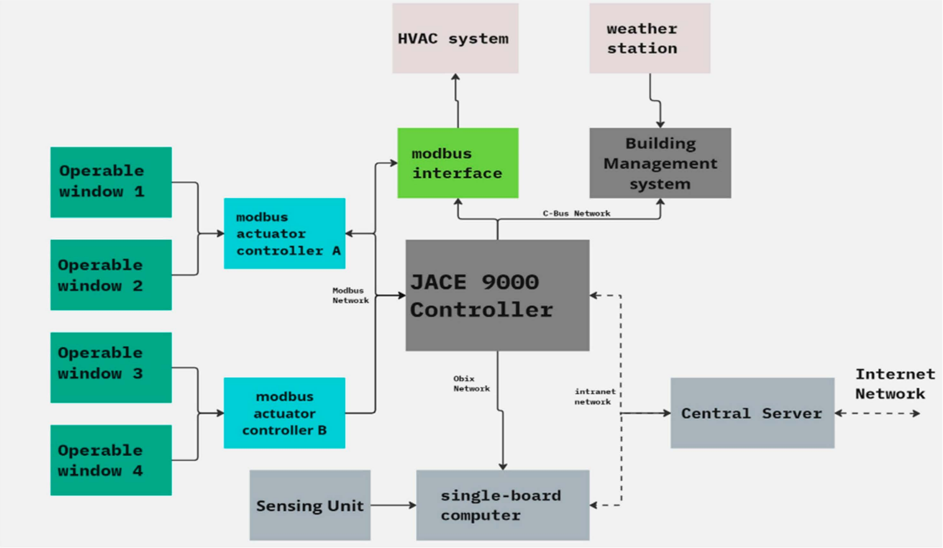

Figure 8. Advanced automated control architecture.

6.2. Semi-Automated Control Systems

In a similar manner to automated systems, semi-automated controls merge NV and MV systems with building automation systems (BAS) to enhance IAQ and energy efficiency [78]. Nonetheless, this system allows occupants to manually intervene in the BAS controls by selecting different operation modes via a control panel situated within the ventilated area [72,81]. As a result, occupants have the ability to modify air volume, temperature, and window openings to satisfy their indoor thermal preferences. This system provides occupants with a degree of autonomy alongside a sense of accountability. Semi-automatic MM controls are not widely utilized in educational institutions, but they can be beneficial in office environments and staff rooms where individuals can be trained to effectively operate the system. It can prove useful if the automated control system fails, during sudden extreme weather changes, or in the event of an unexpected surge in occupancy [83]. While the control system can satisfy the thermal comfort standards of occupants, it may lack energy efficiency due to the tendency of individuals to continuously override the control algorithm [84]. Khatami et al. [29] further asserted that individuals residing in a given space exhibit a heightened cognizance of thermal comfort in comparison to their awareness of IAQ. Consequently, relying solely on the occupants to fully regulate the ventilation apparatus may considerably amplify the potential for substandard IAQ within the building envelope [58].

6.3. Comfort-Oriented Control Strategy

A basic designed temperature control algorithm equipped with thermostats struggles to fulfill thermal comfort requirements [2]. Consequently, thermal comfort indices are referenced in contemporary standards, alongside occupants' perceptions of comfort [77]. Thermal comfort refers to the feeling of contentment within one's thermal surroundings. In reality, it is unrealistic to create a thermal atmosphere in a space that pleases all occupants, as various people possess different metabolisms, clothing choices, and thermal preferences. Thus, the goal of this control strategy is to achieve a degree of comfort that is acceptable to most occupants [81].

The comfort-focused strategy in MMV incorporates window openings to provide occupants with a broader spectrum of indoor comfort levels [87]. Generally, this strategy activates the MMV solely during school hours when the building is occupied and deactivates it after hours to enhance energy efficiency [87]. Nevertheless, the control system can be programmed to precondition the building's envelope prior to occupant arrival and also initiate night cooling via NV in server rooms, which require continuous airflow [88]. The control system aims to anticipate indicators of all potential and subsequent control actions during active periods to identify the optimal solution that consistently maintains the predetermined indoor comfort limits [89].

Indoor comfort standards for schools are relevant to both fully natural and MV systems. Therefore, the MMV comfort-oriented strategy combines both systems within the control algorithm, providing a broader operational margin [52]. Schools situated in colder climates are capable of achieving substantial energy savings exclusively during the off-winter seasons [54]. The PMV index is utilized in cold climates when NV is least effective; however, a proposed controller logic devoid of fixed thresholds can be incorporated to recalculate daily parameter values and shifts in the occupant's acceptability bands for adaptive comfort to enhance future operations. Given that perfect external temperature conditions for NV primarily hinges at the time of the year, the effectiveness of this fixed-threshold approach may not be adequate [26]. Moreover, researchers have started to explore variable-threshold methods, which necessitate periodic adjustments based on fluctuations in outdoor climate [81]. Aguilera et al. [88] have proposed a variable-threshold building control methodology grounded in an adaptive comfort paradigm. They conducted simulations of this methodology utilizing meteorological data from five distinct geographical regions. The outcomes revealed that the variable-threshold control methodology yielded a 20% decrease in energy consumption within warm and humid climates, exemplified by Palermo and Tokyo.

6.4. Improving MMV Control

The enhancement of energy efficiency and IAQ in MMV largely depends on the effectiveness of its control systems and the prevailing climatic conditions [78]. Unlike control systems, climatic conditions are beyond one's influence, but control systems can be designed to achieve the desired results [89]. Consequently, researchers place greater emphasis on designing and developing highly responsive control systems that can adapt to fluctuations in both indoor and outdoor environmental factors [80]. Improvements to these control systems in educational facilities can be achieved through comprehensive research, data gathering, and analysis of local climate conditions and occupancy trends within the school building [90].

Furthermore, the integration of sophisticated sensors with multi-parameter and high-resolution capabilities enables detection and response to changes in environmental conditions across various zones in school buildings that utilize zoned ventilation configurations [78]. The implementation of adaptive and predictive algorithms through machine learning and artificial intelligence can optimize ventilation strategies based on historical data, real-time conditions, weather forecasts, and predictive modeling [91]. Additionally, incorporating enhanced occupant feedback mechanisms and user-friendly interfaces will facilitate immediate adjustments for semi-automatic controls or refine future operations for fully automatic systems [92].

Incorporating energy optimization strategies such as dynamic energy modeling allows for the utilization of real-time energy assessments to progressively evaluate and enhance the equilibrium between NV and MV, thereby improving energy savings while ensuring IAQ [93]. The addition of demand-controlled ventilation enhancement features, including infrared cameras or motion detectors, can accurately adjust ventilation rates based on the real occupancy level of the ventilated space [84,94]. Predictive maintenance and regular recommissioning of the control systems ensure that the ventilation systems function efficiently without interruptions [33]. Moreover, establishing long-term performance monitoring will ensure continuous improvement through data analytics [32].

7. Energy Efficiency Potential of Mixed-Mode Ventilation (MMV) Systems

Educational institutions, corporate establishments, and residential accommodations represent approximately 40% of the energy requirements within the European Union [64]. The predominant segment of such energy demands pertains to heating and cooling. Enhancing the efficiency of HVAC systems is projected to attain lowered energy consumption [95]. The MMV system has been identified as the most efficient HVAC configuration when it is efficiently designed and controlled. Through an extensive control and monitoring framework, this system can provide exceptional indoor comfort alongside superior energy performance [68]. The MMV system has the capability of reducing cooling energy usage in educational facilities during daytime hours and achieves even greater reductions in residential settings during the night [96]. The flexibility inherent in this system allows for intermittent ventilation, wherein the system operates in NV mode and activates MV fans only as necessitated by indoor or outdoor environmental conditions. This configuration can realize energy savings ranging from 44% to 62% [97]. Additionally, climatic factors and the thermal efficiency of buildings further impact the extent of energy savings attainable through the MMV system [60].

7.1. Energy Savings Mechanism

The concept of energy savings in the context of MMV emphasizes periods during which MV is either partially or wholly substituted by NV, thereby ensuring that IAQ and thermal comfort remain uncompromised [11]. A considerable amount of energy is saved when the MV system and components are shut off or partially operated for a longer duration during NV modes. The proportion of fully or partially activated NV modes across the year determines the energy gains made and the overall efficiency of the MMV system. The optimization of NV through the implementation of effective control strategies is crucial for attaining the highest levels of energy efficiency within an MMV framework by ensuring an accurate window opening time, duration, and measure [96]. Integration of advanced technologies such as ground source heat pumps and solar collectors can substantially reduce the energy demand of HVAC systems for heating and cooling, resulting in elevated seasonal efficiency ratios [51]. In the absence of these sophisticated technologies and control mechanisms, the influence of extreme weather events on energy utilization can be considerable [97]. For example, Mankibi et al. [98] conducted a comprehensive investigation aimed at identifying optimal control strategies predicated on MMV, with the objective of concurrently ensuring sufficient IAQ while fostering energy efficiency. The findings of the study indicated that the MMV system exhibited increased energy consumption during the winter and spring seasons, while concurrently maintaining optimal IAQ and thermal comfort; it proved to be more efficient in energy usage during the summer months, notwithstanding a marginally elevated CO_2 concentration. In terms of energy conservation, the integration of MMV with control strategies resulted in a remarkable reduction of 90% in energy consumption by the exhaust fan when compared to traditional mechanical exhaust systems, all while sustaining comparable levels of thermal comfort.

The primary challenge in MMV systems is developing the most effective control strategy to attain optimal energy savings and IAQ performance [98]. Formulating an appropriate control model that seamlessly integrates window operations with the conventional HVAC system by establishing the conditions and timeframes that trigger the transition between NV and MV can ensure significant energy savings without sacrificing IAQ and thermal comfort [78]. For instance, Mossolly et al. [80] outlined several control methods and, utilizing an optimization model, pinpointed the finest control strategy, which resulted in the most notable decrease in energy consumption compared to traditional methods, while also meeting indoor climate standards. They reported an 11% energy savings achieved by adjusting the intake–air temperature flow rate, along with an impressive 30.4% reduction when utilizing PMV thresholds rather than temperature, all while concurrently modifying the intake–air flow rate, temperature, and the outdoor air flow rate [80]. Table 2 enlists some studies on MMV energy saving and the results obtained. It is observed that energy savings from MMV come from cooling or heating energy consumption of the HVAC system and intake fans when the NV mode is partially or fully activated.

Table 2. Summary of studies estimating energy-saving potential of MMV systems.

Study	Location	Method	Study Period	Criteria for Energy Performance	Energy-Saving Potential of MMV Strategy
Emmerich et al. [99]	Boston, LA, Miami, Minneapolis, San Francisco	Simulation	February, April and July	Fan energy consumption (heating and cooling)	LA: 94% cooling/heating load and 97% fan energy saving SF: 45% cooling/heating load and 93% fan energy saving
Wang et al. [100]	Chicago (humid continental), Houston (humid subtropical), and San Fransisco (Mediterranean mild)	Simulation, focusing on MM control strategy (change-over and concurrent)	Summer (Jun–Aug)	HVAC energy consumption	MMV approaches reduced HVAC energy consumption by 17–47% relative to conventional VAV system
Zhao et al. [101]	Pittsburgh, USA	Simulation	One week during swing season	HVAC system energy consumption	34% reduction in HVAC energy consumption
Pesic et al. [102]	Terrassa, Barcelona, and Tarragona, Spain (Mediterranean climate)	Simulation, comparing five MMV strategies against full MV performance	Summer season, April to October	NV hours energy savings	Barcelona 20–41% Terrassa 16–28% Tarragona 10–28%
Gokarakonda et al. [103]	Three climate zones of India: warm and humid (Visakhapatnam), hot and dry (Surat), composite (Bhopal)	Simulation, investigating design and control parameters	One year	NV hours, cooling energy consumption	10% utilization of NV in total occupied hours
Chen et al. [104]	-	Simulation, effects of local climate on NV potential	One year	NV operating hours	Approximately 50% reduction in total cooling energy consumption
Malkawi et al. [105]	Cambridge, USA	CFD Simulation assessing the adequacy of wind- and buoyancy-driven NV	One year	Cooling energy consumption	About 5% to 10% savings in cooling energy consumption
Sanchez-García et al. [106]	Seville, Spain (hot summer and mild winter)	field Observations and empirical data-based simulation	One year	Cooling/heating energy consumption	Energy consumption reduction of about 60% with adaptive control
Tognon et al. [64]	Helsinki, Venice, Rome	A dynamic simulation model with TRNSYS and CONTAM	one year	heating/cooling energy consumption	MV to NV switch-cooling demand decreased by 24%, 31%, 11% in Rome, Vernice, Helsinki. Heating savings = 40%, 22%, 30%

7.2. Advanced Control Strategies

The aim of advanced control strategies in MMV systems is to attain the desired balance between IAQ, thermal comfort, and energy efficiency, depending on the utilization of the ventilated area and the established target parameters [78]. Placing a greater emphasis on energy efficiency can adversely impact IAQ and thermal comfort, and the opposite is equally true [107]. Thus, investigating methods to minimize energy waste and capitalize on every small benefit represents the most effective control strategy [78]. Advanced MMV control strategies can provide a customized approach to airflow by considering both indoor and outdoor environmental conditions and potential fluctuations to effectively utilize the natural air inflow at the appropriate levels and times, thereby supporting the HVAC system's performance [108]. Advanced controls can also be combined with self-learning artificial intelligence tools capable of adapting based on operational data to enhance the control algorithms. A well-crafted control strategy can considerably abate or even eradicate the need for MV for most of the year without sacrificing the indoor environment quality [109]. A foundational control algorithm can be designed to manage the transition between NV and MV and also establish the timing and extent of window openings based on temperature and carbon dioxide concentration levels. Additional adaptable control parameters can be incorporated to boost control efficiency.

Several advanced MMV control strategies exist; the most common and effective strategies suggested in various studies are shown in Figure 9. The type, use, design, and location of a building are some factors that determine the optimal advanced control strategy to implement. In most advanced controls, the basic control algorithm is enhanced by incorporating CO_2, particulate matter, humidity, and various parameter-level sensors that respond to the ventilation rate, ensuring optimal IAQ [80]. The primary task for the mixed-mode control approach is to determine the NV operational range suitable for the local climate [110]. Research indicates that indoor and outdoor temperatures are critical in assessing the efficiency of NV, with outdoor and operative temperature being defined as two-dimensional threshold parameters for defining the operational range for NV [111]. MMV is skilled at quickly adjusting air volume through window openings and MV fans to meet IAQ and thermal comfort criteria; furthermore, during full NV mode, occupants can override operable windows, giving them the ability to adjust windows based on their indoor environmental preferences [34].

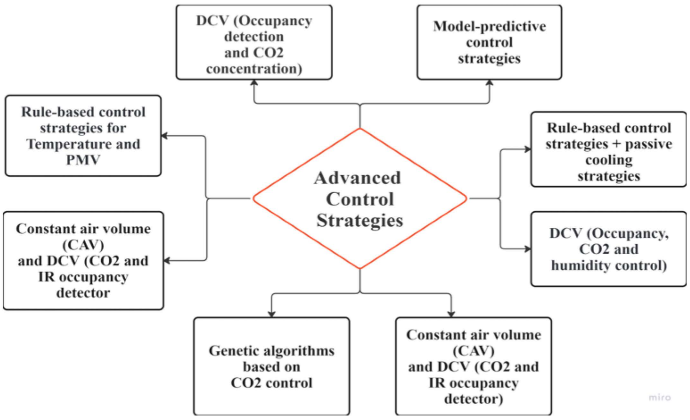

Figure 9. Advanced control strategies for mixed-mode ventilation.

7.3. Comparative Energy Savings Across Different Climates

Research has shown that MMV can significantly improve IAQ in educational settings [47]. The design and implementation of the hybrid system allows for the use of either NV, MV, or a blend of both modes at any time, depending on the indoor environmental conditions [48]. Blending MV with NV can result in better IAQ, especially when advanced control systems and sensors are incorporated [49]. There are significant decreases in CO_2

levels when comparing a naturally ventilated area of a building to a mechanically ventilated area [31]. NV allows for cross-ventilation based on the building's architectural design, thereby improving air movement when these two-ventilation types are effectively integrated [50].

The efficiency of MMV systems is significantly affected by the local climatic conditions of the building [27]. In regions with temperate climates, NV can be extensively employed, leading to substantial energy conservation, whereas in more severe climates, the dependence on mechanical systems escalates, relegating NV to a supplementary role [110]. This makes temperate climatic regions the most suitable for MMV, and higher energy savings can be attained. Other climates may integrate MMV systems with heat recovery, or underground cooling can enhance energy saving by reducing the heating or cooling load on the HVAC system during harsh winters or extremely hot summers. Table 3 illustrates a summary of results from relevant studies reviewed.

Table 3. Summary of studies of MMV energy savings in different climates.

Study	Location	Climate	MMV System	Energy Savings
Hommod et al. [112]	Kuala Lumpur	Warm humid	MMV with cross-ventilation	27–29% energy savings
Ezzeldina et al. [113]	Egypt	Hot arid	MMV with underground cooling	50% hybrid energy efficiency
Cui et al. [114]	Shanghai	Sub-tropic	Integrated radiant cooling panel with an airbox	7.1% increase in cooling capacity
Sultana et al. [115]	Canada	Temperate	MMV with Scheduled automatic window opening	10–20% energy savings
Hamdy et al. [116]	Glasglow	Temperate	Three MMV strategies with chimney vent for cross ventilation	68% MV fan energy savings
Steiger et al. [117]	Munich, Copenhagen, London	Temperate	Automatic NV, MMV with heat recovery	60–70% energy savings

7.4. Renewable Energy Integration

Renewable energy sources can serve as a pathway to alleviate the energy demands of MV systems on traditional energy sources [77,118]. This concept is likely feasible in many schools and ought to be explored as a strategy for minimizing the carbon footprint of these institutions while enhancing energy efficiency [119]. Installing PV panels or small wind turbines on the rooftops or facades of school buildings can generate electricity to power fans, sensors, and actuators that are essential components of MMV systems [120]. Additionally, solar thermal collectors and geothermal heat pumps can effectively precondition incoming air during the winter months, thereby decreasing the reliance on mechanical heating or cooling [62,118,121]. Despite the drawback of high investment costs and dependence on weather conditions for these renewable energy technologies, their long-term advantages and cost savings ensure a prompt return on investment and accelerate the sustainability and carbon neutrality of educational facilities.

8. Conclusions

This review underscores the crucial function that MMV systems can serve in enhancing IAQ and energy efficiency within schools. MMV systems provide a harmonious solution by combining NV and MV techniques, allowing them to be flexible across different climatic conditions and occupancy rates. This review concludes with the following points.

I. MMV systems can considerably improve IAQ, which has a direct influence on the health, cognitive abilities, and overall well-being of both students and staff. Furthermore, the energy-saving capabilities of MMV, when designed and integrated effectively, can aid in lowering operational expenses and the environmental impact of educational institutions.

II. By strategically employing sensors, automated controls, and real-time data to design and improve the control algorithm of MMV systems, one can effectively optimize air circulation, improve energy savings, and uphold ideal thermal comfort and IAQ benchmarks.
III. Energy savings in MMV emphasize periods during which MV is either partially or wholly substituted by NV. The overall duration of NV modes, either partial or full, accounts for the level of energy savings from MV fans, chillers, and heat pumps, etc.
IV. Climate is a major contributing factor to MMV energy efficiency. It was revealed that the system is highly efficient in temperate climates because the NV mode is sufficiently utilized. Studies in temperate climatic regions averaged energy saving between 60 and 70%.
V. An effective control strategy and the integration of MMV systems can determine the overall efficiency of the system. By utilizing cutting-edge technologies like artificial intelligence, advanced control system design, integration into building architecture, and renewable energy integration, schools can benefit from MMV systems.

In summary, the implementation of MMV systems in schools presents a practical means of reconciling energy efficiency with IAQ to maintain a healthy and effective learning environment. Nonetheless, developing a customized control algorithm and strategy that is based on a study of the local climate and ventilation requirements is expensive and time consuming. This poses a challenge to the application of MMV in schools. A solution could be to develop an advanced adaptive control algorithm framework to form the basis on which algorithms can be easily developed when area-specific data are obtained. This will be a major breakthrough for the application of MMV systems, and it is an area that can be considered for future research.

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