

Potential and practical management of hybrid ventilation in buildings

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ABSTRACT

Ventilative cooling technologies have the potential to be an effective measure to reduce buildings energy consumption, by meeting some or all of the cooling requirement of a building without the need for mechanical cooling. Mixed-Mode (MM) buildings utilise both natural and mechanical cooling systems to meet their thermal energy demand. These buildings are able to guarantee that thermal comfort conditions are maintained, whilst exploiting the cooling potential provided by the climate. Effective management of the cooling systems in MM buildings is important to ensure that comfort is maintained and free cooling is exploited when available. While the implementation of hybrid ventilation systems is becoming more common, the current industrial and academic research state-of-the-art provide different and sometimes contrasting approaches to the management and evaluation of MM buildings. The current review provides an overview of studies into MM buildings performed in the last 10 years, analyzing in detail key factors that determine the potential of a building to save energy, including simulations inputs assumption, comfort standard used for evaluation, building and Heating, Ventilation and Air Conditioning (HVAC) systems typologies and control strategy employed. A detailed analysis of the papers which had a focus on methods for control of hybrid ventilation system was undertaken. This highlighted the importance of coordination between systems to ensure operational effectiveness and showing that while the majority of the studies employed classical control techniques, predictive control methods were the most investigated approaches to fully exploit the potential efficiency of MM buildings.

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Contents

1. Introduction	2
1.1. Previous reviews and gap	3
2. Methodology	3
2.1. Search strategy	3
3. Preliminary analysis of literature	3
3.1. Summary of reviewed studies	3
3.2. Building types	4
3.3. Experimental vs simulation numbers	5
4. Hybrid ventilation potential – Simulation studies	5
4.1. Simulation tools	5
4.2. Simulation methods and assumptions	6
4.3. Results on ventilation potential and energy savings	7
5. Hybrid ventilation potential – Experimental studies	8
6. Hybrid ventilation – Importance of controls	9
6.1. Occupant comfort and controlled variables	9
6.2. Control methods	11
7. Discussion	11

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Acronyms

AC	Air-conditioned	PMV	Predicted Mean Vote
MM	Mixed-Mode	IEQ	Indoor Environmental Quality
BMCS	Building Management and Control Systems	BPS	Building Performance Simulation
HVAC	Heating, Ventilation and Air Conditioning	MVHR	Mechanical Ventilation Heat Recovery
NV	Natural Ventilation	WWR	Window-to-Wall Ratio
MPC	Model Predictive Control		
RBC	Rule-Based Control		

8. Conclusions.....	13
Declaration of Competing Interest	13
References	13

1. Introduction

Global energy demand has been increasing, with associated impacts on anthropogenic climate change. Buildings are one of the biggest contributors to this consumption, and Heating, Ventilation and Air Conditioning (HVAC), is a major energy end-use in buildings, in particular for space cooling. It is therefore a priority to promote the mitigation of buildings' cooling demand; one promising solution is the integration of ventilative cooling solutions.

Ventilation is the process whereby stagnant indoor air is replaced by fresh outdoor air. It is a critical process in building operation to maintain an appropriate indoor air quality by removing the contaminants generated in the indoor environment. When controlled effectively, ventilation can also provide an opportunity to reduce the energy required to maintain thermal comfort in a building, by utilising free cooling from the outdoor air when conditions are suitable. This is known as ventilative cooling.

Previous studies have highlighted that ventilative cooling solutions can provide a reduction in cooling demand for portions of the year [1–3], but that fully natural ventilated buildings might not be able to maintain thermal comfort conditions throughout the year. Further, the ventilative cooling potential is dependant on appropriate local climatic conditions, and it will not be usefully applied in many climate zones. For instance, a review on the influence of atrium design parameters on thermal conditions [4] found that buoyancy-driven ventilation alone has an insignificant effect on the atria thermal conditions in hot and humid climates, thereby the used of hybrid systems such as pressurized ventilation were encouraged. An another study by Ezzeldin and Rees [5] studied the performance of multiple cooling strategies in an office building modelled with different levels of internal heat gain in arid climates. Results showed that, despite Natural Ventilation (NV) could not be used during occupied periods in summer it could keep thermal comfort from 37% to 57% of the occupied time over the year depending on the location.

Mixed-Mode (MM) buildings, or buildings with hybrid ventilation, combine natural ventilation systems with mechanical cooling systems. Hybrid systems aim to exploit free cooling from the mixing of the outdoor air with the indoor one as often as possible, whilst using mechanical cooling to ensure thermal comfort is maintained during times when outdoor conditions are not appropriate for ventilative cooling.

However, management of MM buildings is more challenging due to the nature of the MM operation and controls. Firstly, the control of natural ventilation systems is more complicated than mechanical systems, as these systems rely on outdoor air conditions to be better than the indoor ones in terms of temperature, humidity and contaminants levels, and often to have enough driving forces, relying on good wind speed and direction to enable an effective air flow through the building. Secondly, the operation of MM combines mechanical systems with NV, and its combination can occur a) concurrently, where NV and mechanical systems operate at the same space and time, b) changing-over, where both NV and Air-conditioned (AC) operate at the same space but at different times in interchanging MM or in seasonal MM, or c) zoning-mode, where the NV and AC are operating at different spaces but at the same time [6]. Lastly, MM buildings need to effectively coordinate mechanical and natural ventilation systems, to ensure comfort is maintained while avoiding energy wastage due to opening of windows at the wrong time or set-points. A review by Feng et al. [7] highlighted the importance of integrating the passive strategies together with the active systems in the effective operation of net zero energy buildings to achieve the energy reduction targets.

The assessment of occupants' thermal comfort in MM buildings is also a challenging task. Rijal et al. [8] found that MM buildings were mostly managed thermally as if the occupants were in a naturally ventilated building, providing additional mechanical cooling if needed, rather than as in a normal air-conditioned building. While for fully naturally ventilated buildings the adaptive thermal comfort theory should apply [9–12], in mechanically ventilated buildings another comfort theory is valid, based on the Predicted Mean Vote (PMV), which is used to estimate occupant thermal comfort in conditioned environments [9,10,12,13].

Industry practitioners typically use a tailored approach in devising regulation strategies for MM buildings, as each building mechanical and natural ventilation system is different and there is a lack of a standard method to define the appropriate comfort ranges. Standards still conservatively categorize MM buildings as fully mechanically conditioned environments, constraining them to operate in the more restrictive PMV range compared to wider adaptive thermal comfort range.

This paper therefore aims at providing a comprehensive overview of the current research approaches on the thermal management of MM buildings. This study reports where and when the studies were performed, what building type and in which climatic

context was analysed, which assumptions were made in terms of building, internal gains, set-points, etc., which comfort standard was used to evaluate the indoor thermal conditions, what mechanical system was coordinated with the natural one and when they were employed (i.e. day or night), and finally which control strategy was employed and what variables were used to control the buildings. The reported minimum and maximum energy savings were also analysed, for both simulated and experimental studies, providing a snapshot of the expected effectiveness of such systems in various climate zones.

1.1. Previous reviews and gap

Ventilation systems and techniques for MM buildings have been extensively reviewed. In some cases, control systems for the MM building are also included. For instance, Salcido et al. [14] reviewed studies assessing the potential of MM ventilation systems in office buildings. It was found that the maximum potential energy savings with optimised window operation varied from 20% to 70% depending on climate. The assessment method to evaluate the performance of the MM buildings was highlighted as a typical source of discrepancy in the energy results due to simulation assumptions not replicating reality.

The reviews undertaken on improving the energy efficiency of existing buildings [15,16] highlighted the potential for GHG reductions through the use of hybrid ventilation strategies provided that: a) control settings were included in building regulations for MM and AC buildings [15] and b) barriers such as lack of information, lack of understanding and safety were overcome [16]. The development of efficient hybrid ventilation systems together with an improved thermal envelope was mentioned by [17] as an avenue to unleash the energy efficiency potential of buildings.

Night ventilation strategies are a popular ventilative cooling technique [18,19]. In [18], the effectiveness and limitations of night ventilation across climates were explored. The review grouped the parameters impacting natural ventilation performance into three categories, namely climate dependant parameters (e.g. outdoor temperature), building parameters (e.g. internal heat gains) and technical parameters (e.g. control algorithms). Santamouris et al. [19] reported the applicability of night ventilation for different building types in multiple studies. Based on these studies, they concluded that night ventilation along with other passive cooling techniques could significantly decrease the cooling load of thermostatically controlled buildings.

A review on the development of energy-efficient methods for ventilation in buildings was presented by [20]. Their review suggested that considerable cooling savings can be achieved by using mixed-mode ventilation, particularly when ventilation control strategies were also integrated. The uncertainty around control strategies being able to provide an improvement on hybrid ventilation systems in real life was highlighted as a short coming.

In [21] the performance of smart ventilation strategies using controls mostly based on Indoor Environmental Quality (IEQ) parameters or outdoor temperature for residential buildings was examined. Their literature findings showed the potential to save up to 60% of the energy used as well as less favorable results with 26% over-consumption in some cases via controlled MM ventilation. They concluded that, despite the potential of smart ventilation, it is still an emerging strategy, with limited research on automated ventilation strategies for residential buildings.

The review by [22] on the implementation of natural ventilation highlighted the importance of automated ventilation for MM buildings; it was suggested that ventilation controls are the only avenue to reach the full ventilative cooling potential for MM buildings. However, to date, there are no review papers on different building controls employed in MM buildings.

All of the above reviews considered thermal comfort as a fundamental objective for a successful operation of MM buildings. However, no review on the appropriateness of various thermal comfort assessment methods in MM buildings was identified. The current review explores how MM buildings are being implemented, what controls are being used, and how their thermal performance is being assessed in the absence of a thermal comfort assessment method designed exclusively for MM buildings.

2. Methodology

An extensive search was performed to identify relevant literature concerning the use of or potential for hybrid ventilation in buildings, and methods used for control and management within the ScienceDirect and Scopus databases.

2.1. Search strategy

A search for literature available within Science Direct database was completed on the 14th of February 2020 using the following terms:

“potential” and “energy” and (“buildings” or “building”) and (“hybrid ventilation” or “mixed-mode ventilation” or “mixed mode ventilation” or “mixed-mode building” or “mixed mode building”). This combination of search terms resulted in 404 papers. These papers were then screened (Title, Abstracts and Keywords) based on the following eligibility and exclusion criteria:

- Studies published in peer-reviewed academic journals;
- Studies available in English;
- Studies published since 2010;
- Studies that considered Mixed-Mode buildings (i.e. excluding studies that focused only on fully naturally or mechanically ventilated buildings);
- Studies that assessed the effectiveness of MM building with respect to occupant thermal comfort;
- Studies that assessed the effectiveness of different control strategies on MM building;
- Any geographic location; and
- Full source text available.

The screening process undertaken to review the papers in this study is presented in the flowchart in Fig. 1.

Following screening, 214 papers were reviewed in full. Of these, 96 were found to be relevant and included in the final review. The same search was repeated in Scopus and 2 relevant additional papers were added to the review.

3. Preliminary analysis of literature

This section summarises the trends, in terms of location, publication year, typology of case study building evaluated, comfort standards employed and methods used, in studies conducted in the past ten years which have assessed the performance of MM buildings.

3.1. Summary of reviewed studies

The location of the studies performed on MM buildings is presented in the map in Fig. 2, where the intensity of colour of each country is related to the number of papers published in that region. It can be noticed that the majority of the studies were performed using case study buildings in the United States of America, China and Australia (darker blue), but the studies also cover several other countries in Europe, North-African, South-American countries,

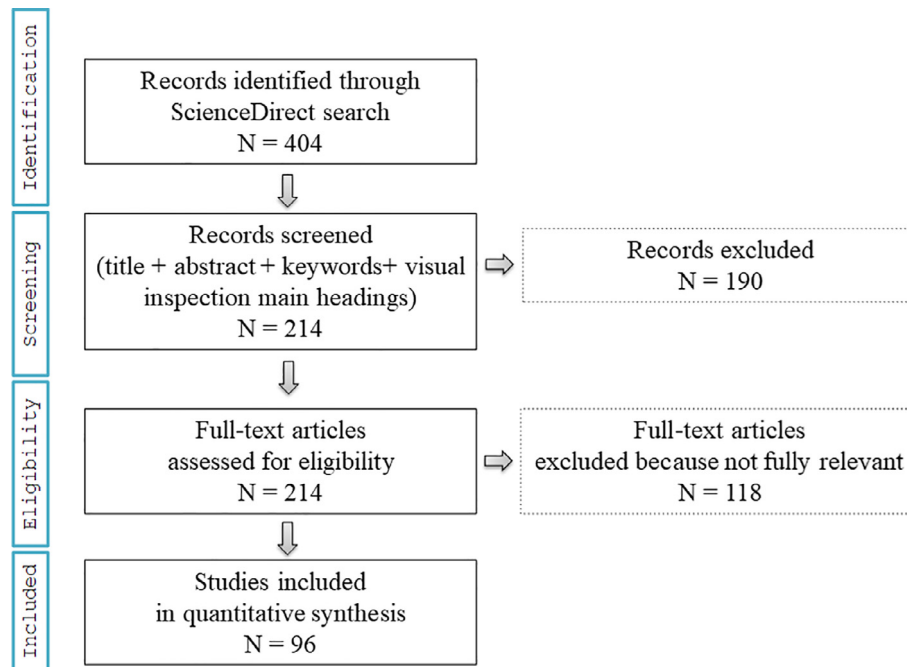


Fig. 1. Diagram of the systematic review process performed in this study.

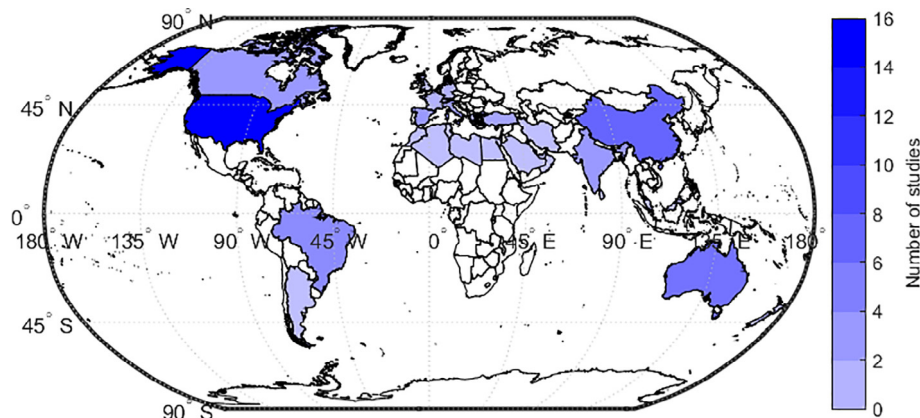


Fig. 2. Map of mixed-mode building studies.

India and Canada. The geographical distribution of papers is probably related to the climate typologies that each country features, where a typical building needs cooling for a significant portion of the year, but at the same time the climate offer the possibility of exploiting the ventilative cooling solutions, which are not feasible in regions with extreme climates (e.g. equatorial locations). The number of studies that report energy saving from the implementation of a hybrid ventilation strategy for each climate zone is reported in Fig. 10 in Section 5. The Köppen climate classification is employed. This classification is the most widely used worldwide, and uses a three letter code to categorise climates according to main climate, precipitation and temperature. The first letter divides the climates into five zones, namely (A) equatorial, (B) arid, (C) warm temperate, (D) snow and (E) polar. Climates are further subdivided based on precipitation, defined by the second letter in the classification (e.g. (f) fully humid, (s) dry summer, (w) dry winter). The third letter categorises based on the air temperature (e.g. Dfc for snow, fully humid with cool summer). Full details of the classification system can be found in Ref. [23]. In Section 5, it can be seen that the climates where there is more perceived value in

implementing ventilative cooling solutions at a design stage are Csa (warm temperate, dry and hot summer - 15 studies) and Cfa (warm temperate, humid and hot summer - 13 studies), followed by Csb (warm temperate, dry and warm summer - 5 studies), Csc climates (warm temperate, dry and cool summer - 4 studies) and Bwh (Hot arid, dry winter - 4 studies).

The number of scientific publications concerning the evaluation and control of MM building has increased over the last ten years (Fig. 3), highlighting the interest of the scientific community in this topic, with the publication numbers particularly growing in the second half of the decade. The number of papers focusing on the management and control of MM buildings controls has followed a similar trend, as highlighted in green in Fig. 3. The recent review on control strategies by [24] underlined that the use of control strategies with HVAC technologies are increasingly important in building energy efficiency and indoor environment quality research. The highest number of papers published concerning the performance of MM buildings was recorded in 2019, the last full year presented in this review. It should be noted that papers from only the first couple of months of 2020 were included in this

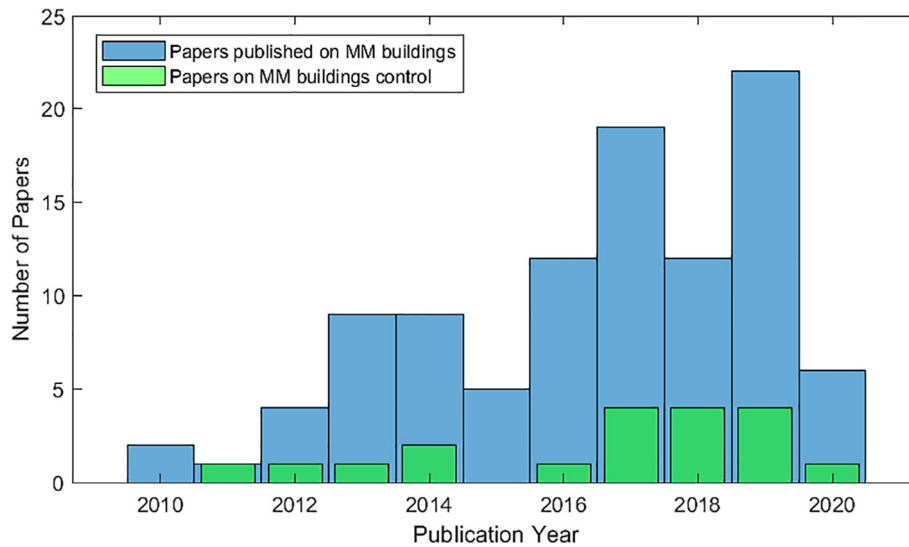


Fig. 3. Number of publications per year on mixed-mode building performance.

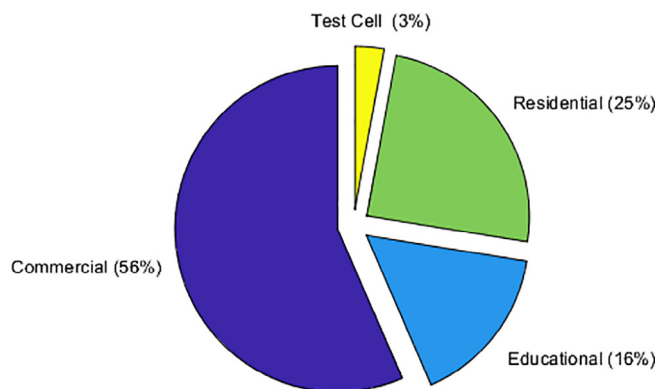


Fig. 4. Typologies of buildings studied.

review, and the number of papers published on this topic in 2020 might be higher than 2019.

3.2. Building types

An overview of the MM building typologies studied in the papers analysed in this review is presented in Fig. 4. Over half of the studies (56%) were conducted on commercial buildings, followed by residential (25%), educational (16%) and test cells (3%). This is not a surprising result, as commercial buildings are typically good candidates for the integration of hybrid ventilation systems for several reasons. Commercial buildings generally have higher internal heat gains that can potentially be offset through natural ventilation, and they are also more likely to have a Building Management and Control Systems (BMCS) capable of effectively coordinating the mechanical and natural ventilation systems. Residential buildings are more commonly MM, as they typically have operable windows to allow natural ventilation of the building, as well as mechanical cooling. However these systems are generally managed by the occupants, rather than a BMCS.

3.3. Experimental vs simulation numbers

Most of the MM buildings studies reviewed for the current paper relied on Building Performance Simulation (BPS) rather than an experimental monitoring campaign, as shown in Fig. 5. Simulation

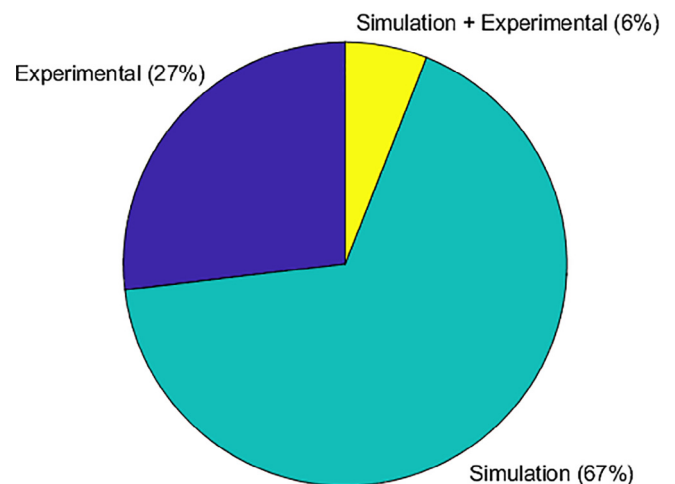


Fig. 5. Fraction of Simulation and Experimental studies.

were significantly more frequently adopted compared to experimental campaigns (67% vs 28%) and the combination of both methods was rarely used (only 6% of the total studies). This is probably due to the difficulty of quantifying the net cooling reduction achieved by introducing the NV component in the ventilation strategy of MM building experimentally. This is mostly because an experimental test of a buildings performance with and without NV implemented can never be identically repeated on the same building with the same weather conditions. One of the few studies that undertook both the an experimental campaign and a supporting simulation study was [25], where the authors evaluated the energy performance of an all air system, a decentralized ventilation and centralized ventilation system utilising experimental data and numerical methods. Their results indicated that the fan-assisted NV systems and decentralized ventilation could be effectively used for a large portion of the year (22–32%) in European climatic conditions.

4. Hybrid ventilation potential – Simulation studies

This section of the paper analyses the tools, assumptions, quantification methods and estimated cooling demand reduction reported in the simulation studies.

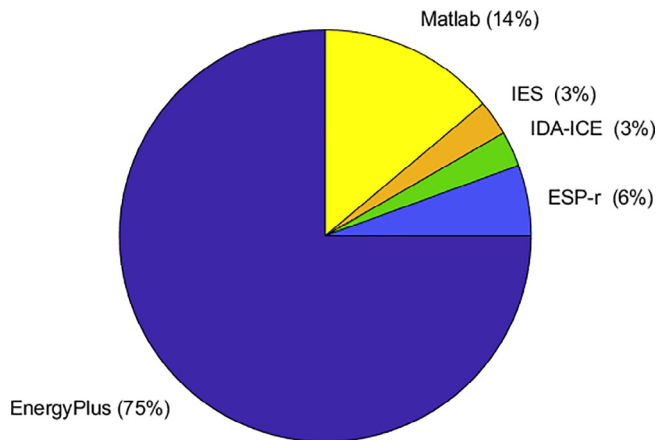


Fig. 6. Tools used in the simulation studies.

4.1. Simulation tools

The most popular BPS tool for MM building thermal behaviour simulation and energy consumption estimation was EnergyPlus, employed by 75% of the surveyed studies, as presented in Fig. 6. EnergyPlus was typically employed to evaluate the difference in energy performance of a MM building under the same external conditions when some key parameters were altered. Commonly tested scenarios were:

- Building design parameters such as window opening area, insulation, and thermal mass (e.g. [26]) or window-to-wall ratio, shading or floor height for example in [27] or different archetypes as [28];
- HVAC type; for example in [28] archetype buildings with central air conditioning systems were compared to buildings with MM systems;
- HVAC and natural ventilation control strategies, rules for operating modes selection, schedules and temperature set-points (e.g. in [29–32]);
- Climate conditions, varying location and/or altering weather representation to account for future climate change, as in [33,34];
- Occupant behaviour and measures to influence it (e.g. in [35]);
- Combinations of different measures and strategies affecting occupant behaviour (e.g. lighting utilisation, occupant density, etc.), comfort criteria, building design parameters and hybrid ventilation control strategies ([36–40,5,41]).

Studies that employed similar BPS tools to EnergyPlus, such as IES (3%), IDA-ICE (3%) and ESP-r (6%), generally had similar simulation objectives. For example Taleb et al. [42] used IES to assess different combinations of active cooling systems and natural passive ventilation strategies in a residential villa in Dubai. They showed that the combination of scheduled HVAC and night time ventilation resulted in a more comfortable temperature compared to only using the mechanical system.

Other studies (e.g. [43–45]) utilised BPS tools to investigate different aspects of MM ventilation, such as the evaluation of the expected overheating hours for a passive house in the Mediterranean climate ([43]). In this study the operation of a house with a Mechanical Ventilation Heat Recovery (MVHR) system was assessed, comparing MVHR only operation, and in combination with a MM ventilation strategy and building envelope modifications. The envelope modifications (reduction of the overall R-value of the envelope) and the MM ventilation strategies resulted

in a 60% reduction of overheating time compared to the base case building. In [44], the uncertainties from climate, building properties and operation were applied to investigate the potential for MM buildings ventilation. Results reported the distribution of savings for three different locations, highlighting the importance of providing non-deterministic savings. Another investigation by [45] examined the influence of outdoor air quality on natural ventilation. As this influences the operation of the building, a more detailed discussion on this study can be found in Section 6.

The remaining 14% of the simulation studies employed Matlab. These studies were mostly focused on evaluating different control strategies for MM buildings (e.g. [46–48]). For example, Tong et al. [49] used Matlab to develop a boundary layer model for estimating the vertical profiles of meteorological variables. This model was then used to estimate the NV potential for fully naturally ventilated or MM high-rise buildings.

4.2. Simulation methods and assumptions

In the reviewed studies the evaluation of the performance of MM buildings was typically undertaken by comparing the estimated energy consumption of the building using hybrid ventilation, with the estimated consumption of the building operating with only mechanical systems (i.e. no NV). In these cases, the case study building(s) was simulated using BPS, and the factors to be analysed were varied in multiple model realisations, and the results compared. In studies using this method of estimating energy savings, the assumptions made when modelling unknown or uncertain parameters in a building are of critical importance. Daly et al. [50] showed that the predicted energy consumption in a commercial building can vary substantial when modelled with a range of reasonable assumptions from various reputable sources. Studies typically try to mitigate this by comparison to a baseline model with the same assumption, however caution should always be used when interpreting these results as the starting assumption can influence findings (e.g. higher internal gains assumptions will likely lead to better performance of MM buildings). Variability in starting assumptions also makes it more difficult to compare results from different studies.

A study by Giouri et al. [51] found that assumptions related to the cooling set-point had the highest impact on annual energy demand, energy production and adaptive thermal comfort levels for a high rise office building. The effect of assumed air flow rate, NV indoor set-point temperature and indoor-outdoor temperature difference on the energy performance of residential buildings in the Mediterranean region was evaluated by [52]. Results suggested that the ventilation specifications that minimize air-conditioning energy consumption fall within similar values for all the evaluated locations: ventilation rates of at least 10 air changes per hour, a minimum indoor set-point for ventilation slightly below the building's cooling set-point, and a low indoor-to-outdoor temperature difference. It was also found that, in lower latitudes, the buildings' energy performance tended to be similar between them irrespective of their geometry (e.g. number of stories, openings, etc.) and orientation.

The heating and cooling set-points used in the surveyed papers are presented in Fig. 7, where it can be seen that there is more variance in the assumed cooling set-point than heating. In approximately 75% of the cases, the heating set-point used for the simulation of the building model was between 20 °C and 21 °C, with almost half of all studies using 21 °C. For cooling set-point the spread was greater, with at least 15% of studies using 23 °C, 24 °C, 25 °C or 26 °C. This data is also presented in the box-plot in Fig. 7, showing the spread of the heating and cooling set-points. The median heating set-point was 20.5 °C and the median cooling set-point was 25 °C.

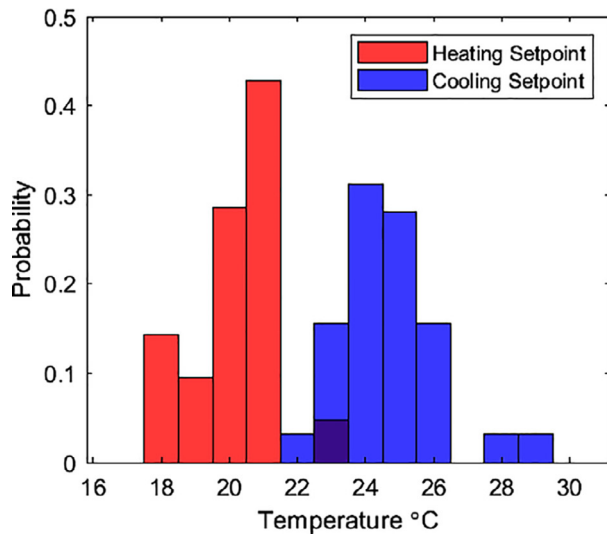


Fig. 7. Heating and cooling set-points used in the simulation studies.

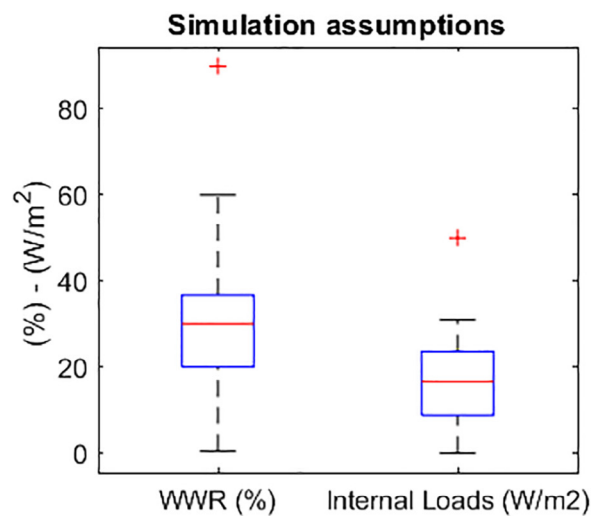
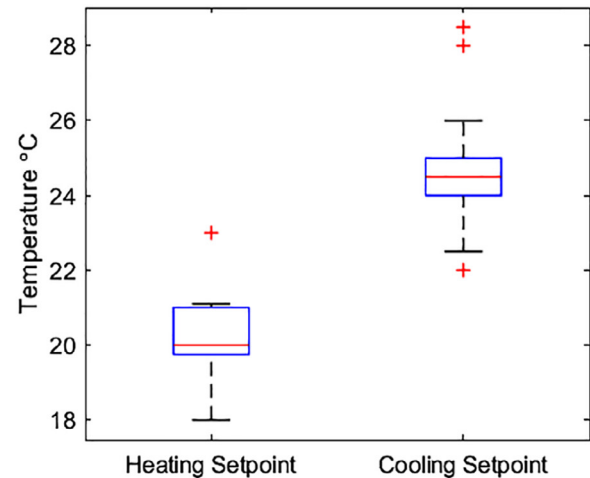
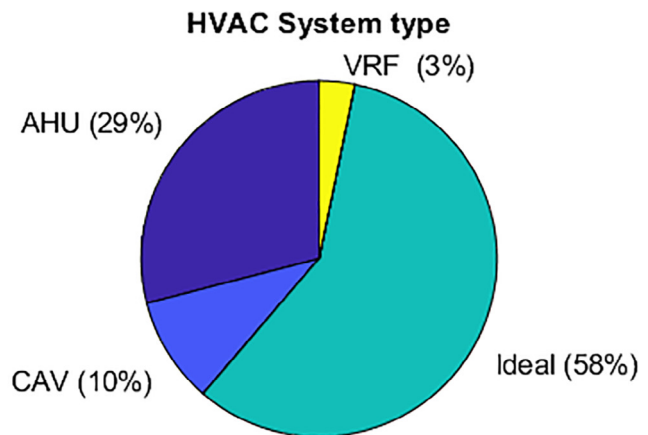


Fig. 8. Window to Wall Ratio, Internal Gains (equipment + lighting) and HVAC system representation used in the simulation studies.



A buildings Window-to-Wall Ratio (WWR) and the internal loads profile are highly influential assumptions for buildings attempting to offset cooling demand using hybrid ventilation. Any increase to heat gain in a building increases the potential time periods in which they can be usefully offset using the outdoor air, and therefore the potential energy savings. As presented in Fig. 8, the reviewed papers mostly examined building with a WWR between 20 and 35%, with a median of 30%. Internal loads were typically between 10 and 25 W/m^2 , with a median of 20 W/m^2 . The wide spread of values in these assumptions can be explained by the different building typologies reviewed in this paper, as shown in Fig. 4 in Section 3.2.

Another important assumption is the type of HVAC system used in the simulation. The HVAC employed in the reviewed simulation studies are shown in Fig. 8. More than half of the research papers (58%) did not include a detailed representation of a HVAC system, but rather relied on the BPS program to create an ideal system to quantify the heating and cooling demands. The majority of the papers that modelled the HVAC system in detail described a system with a Air Handling Unit (AHU) and Variable Air Volume (VAV) boxes (29%), with some modelling a Constant Air Volume

(CAV) system (10%) or a Variable Refrigerant Flow (VRF) system (3%).

The operation schedules that were utilised in the studies reviewed for the operation of mechanical and natural ventilation are shown in Fig. 9. The most prevalent schedule are for HVAC use is daytime operation only (for example [53–55]), as in all most commercial and educational buildings comfort is only a required to be maintained during working hours. NV on the other hand was applied at both day time and night time (e.g. [56–58]), as there are obvious advantages to cooling the building fabric at night time. Only a few studies used different schedules for HVAC and NV, such as [59,46,60]. In these cases the NV was scheduled to operate only at night with 24-h HVAC operation except for [46], where the operation of the HVAC was restricted to day time only. The exclusive night time use of HVAC is rare, and only applied to residential buildings. Only one study [61] investigated night time hybrid ventilation by assessing the relationship between the architectural spatial indicators, ventilation performance and energy consumption in a MM residential building. Results demonstrated the energy saving potential of natural ventilation for the hot summer and cold winter climate in China.

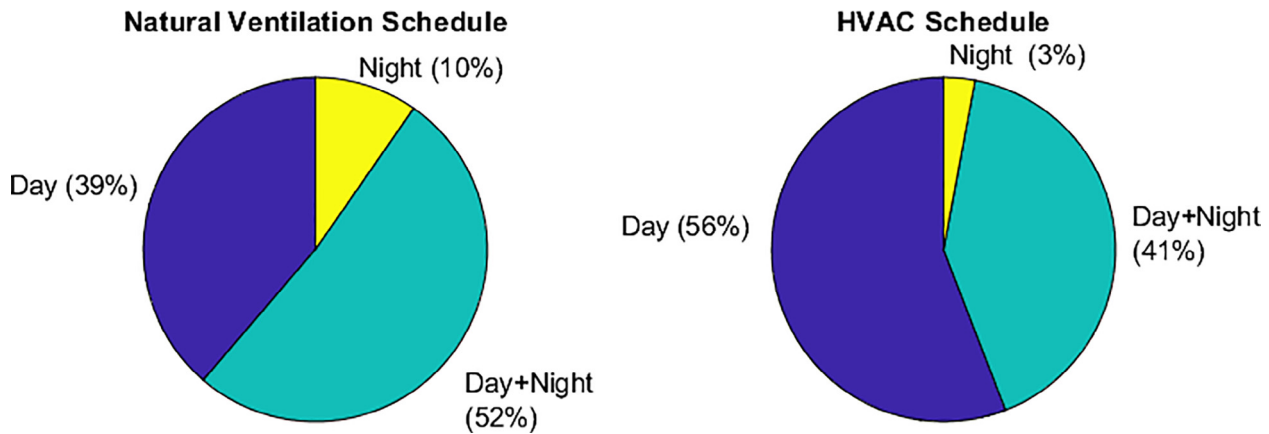


Fig. 9. Mechanical and Natural Ventilation schedules used in the simulation studies.

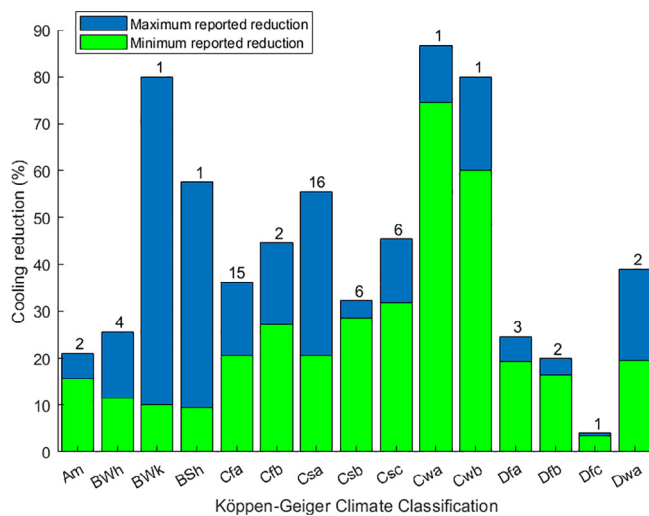


Fig. 10. Minimum and maximum cooling reduction reported by the simulation studies, with sample size.

4.3. Results on ventilation potential and energy savings

Simulation studies generally report a minimum and maximum estimated cooling reduction percentage for each of the case study buildings analysed. As the potential for climatic cooling is mostly impacted by the weather conditions, a summary of the reported results classified per climate zones is presented in Fig. 10. In this figure the average (between the studies in the same climate zone) minimum and maximum reported cooling reduction, together with the sample size, are reported. As mentioned in Section 3.1, most of the studies were performed in Cfa, Csa and Csb climates.

The largest average cooling reduction potential reported corresponds to warm temperate climates with a dry and hot summer (Csa), where the temperate climate allows the use of natural ventilation for a large portion of the year, resulting in an average predicted maximum cooling reduction of 55% (e.g. [34,51,62]). In [34], the impacts of climate change on annual building energy use were investigated through the use of future climate files for five US cities, including cities in Csa. The efficacy of energy efficiency measures (namely adjustment of thermostat set-points, reduced HVAC operation hours, reduced VAV box minimum flow setting, and MM ventilation) on reducing the energy consumption were tested. MM ventilation was found the most effective measure to reduce energy consumption across future climates.

Other climates are less studied, as buildings generally need less need cooling or the climate does not provide as much assistance to natural ventilation systems. Menassa et al. [63] reported for example maximum cooling savings of 20% in a cold continental climate (Dfb), when employing different hybrid ventilation strategies for common spaces in a laboratory building in Wisconsin.

Some studies reported high potential for cooling reduction in temperate climates (Cwa and Cwb) in [56], and the cold arid desert climate (BWk) in [26], as high as 91%, 80% and 80%, respectively. However, these climates zone have only been examined in a single study. The subarctic climate (Dfc) was found to be the one to provide the lowest cooling reduction potential (5%) ([37]); again results are only available from a single study.

5. Hybrid ventilation potential – Experimental studies

Eighteen relevant experimental studies were identified in this review. Of these, eleven were completed in commercial buildings, 6 in educational buildings, and 3 in residential buildings ([64] considered both commercial and educational buildings, and [65] considered both commercial and residential buildings). The largest proportion (8 studies, or 44%) of experimental studies considered a single case study, 6 studies considered 2–5 case studies, 2 considered 6–10, and 2 considered more than 10 buildings. The largest sample sizes were [66], who monitored 11 office buildings with split systems air-conditioners, and [67], who studied 33 office buildings in Brazil.

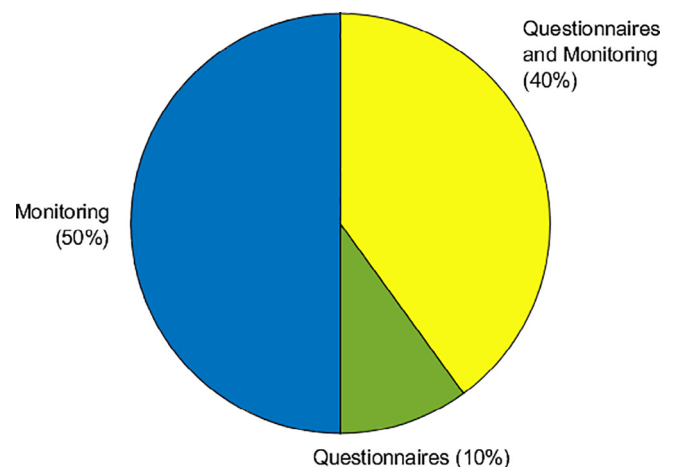


Fig. 11. Tools used in the experimental studies.

Experimental studies relied either on monitoring of environmental conditions, thermal comfort surveys, or a combination of the two methods. The breakdown is presented in Fig. 11. The preferred research tool in the experimental studies was monitoring, which was used by 90% of the researchers. Only a small fraction (10%) used questionnaires in isolation when evaluating MM buildings. 40% of the studies used both monitoring and some form of thermal comfort survey, 6 studies relied on monitoring alone, and 3 on a thermal comfort survey alone.

Of the studies (15) that completed monitoring, The average campaign duration was 7.7 months (SD = 5.7 months). Seven studies monitored for less than 6 months; the average monitoring period for this cohort was approximately 2 months, three were conducted during summer, two during transition seasons, one during winter, and one during both summer and winter. One study monitored for between 6 and 12 months ([68], 11 months), 5 studies monitored for 1 year ([69,70,64,71,72]), and two studies monitored for over 1 year ([73,74]). [74] had the shortest monitoring duration, two periods each of 5 h, in their study characterising the potential energy savings of a hybrid ventilation systems integrating heat storage material. The longest monitoring campaign was [60], who monitored the effectiveness of hybrid ventilation and night cooling strategies for 17 months in an educational building in Canada.

Twelve studies administered some form of thermal comfort questionnaire. [75,67,73] used the Building Use Studies (BUS), many were bespoke such as [76] or [65] which used a bespoke tool integrated into a wearable device (fitbit). Three studies used right-here-right-now questionnaires derived from ASHRAE-sponsored field experiments, i.e. [77,78] used paper-based questionnaires and [68] a phone app. The thermal sensation vote (TSV) based on ASHRAE was employed by [71,72] and based on the EN15251 standard by [64]. [66] used a questionnaire based on the TSV and the thermal adaptation behaviors from ASHRAE.

Experimental results have reported that the adaptive comfort model is more applicable than the PMV-PPD for MM buildings in the follow different scenarios: a) for the building operating in NV [78], b) in a range of elevated outdoor temperatures [64,73], c) only when the windows operation are manual or semi automated [77] or d) due to occupants adaptation by preferring higher temperatures than the predicted by the PPD [66]. The overall perceived comfort for the indoor environment conditions found contradictory results in specific studies, [71] found that HVAC and MM buildings were rated more satisfactory for comfort on the indoor environment conditions than NV buildings while the opposite was concluded in [75]. Nevertheless, a review by Baird [79] on the perception of the users of 60 commercial buildings found that the incorporation of MM together with other features such as atria was rated the highest for comfort and satisfaction.

6. Hybrid ventilation – Importance of controls

Intelligent control of a ventilative cooling system in a mixed-mode building is essential to fully exploit the benefits of free cooling from natural ventilation whilst maintaining equivalent occupant satisfaction to a mechanically ventilated building. When controlling natural ventilation there is the additional constraint that it is necessary to ensure that the external conditions will allow the system to reach the desired control objective. For example, if both the indoor and outdoor temperature are not measured at the same time and used within the control algorithm, it is not possible to know whether the air mixing is providing heating or cooling. Similarly, in a natural ventilation system, the amount of air exchanged is not controllable directly, but is a function of the wind speed, direction and opening of the windows. The current industry

state-of-the-art relies on heuristic rules with fixed schedules to manage mixed-mode buildings. This can lead to a building under-performing from an energy perspective when compared to the design expectations, and/or thermal discomfort for the occupants. Recent studies have focused their attention on the control algorithms and the sensing required to support them. A breakdown of the the control variables and methods used in the papers reviewed are presented in Fig. 12.

6.1. Occupant comfort and controlled variables

The importance of occupant comfort in mixed mode buildings has been subject to several recent studies, highlighting that maintaining a satisfactory indoor environment the combination of natural and mechanical systems requires a more complex sensing and control system than the current practice [80].

Across the globe, multiple International standards for acceptable indoor thermal comfort conditions exist; a recent critical analysis can be found in [81]. The thermal comfort requirements and standards are dependant on the operation of a cooling system (ISO 17772, ASHRAE 55, EN 15251). Strictly speaking, these standards are not applicable for MM buildings. For example, ASHRAE 55 adaptive can only be used in buildings with no heating or cooling system, while ISO 17772 and EN 15251 only apply outside the heating season in buildings with no mechanical cooling. Despite this, and owing to the lack of an applicable standard for MM buildings, adaptive comfort standards were the most widely in the reviewed literature, as seen in Fig. 13. More than half of the studies employed an adaptive model to assess the thermal comfort performance of MM building; 68% on the upper comfort band limit and 63% on the lower limit.

For instance, [5] modelled different cooling strategies in an office building in arid climates. The cooling strategy employed determined which thermal comfort criteria to use; that is for fully air-conditioned offices PMV was used while the ASHRAE adaptive standard was employed for the MM offices. Results showed that to satisfy the PMV comfort criteria required more stringent thermal control when cooling (i.e. lower air set-point temperatures were necessary) than when employing the adaptive comfort model. This meant that the use of the adaptive standard in MM buildings led to an additional reduction in the cooling demand for MM offices, beyond that achieved through the use of natural ventilation. However, the need for further research to assess the applicability of the adaptive comfort model in MM buildings was highlighted.

A study that applied both an adaptive comfort control and a fixed temperature control for MM office buildings was investigated in [41]. In this case, daily set-point temperatures based on the EN 15251:2007 adaptive thermal comfort approach and fixed temperature set-points were modelled and compared. Extending the comfort limits using the adaptive model resulted into a 69% decrease on the energy demand. It was also concluded that more research to test the use of the adaptive comfort model for temperature set-points controls in MM buildings was needed.

Despite the lack of consensus on the most appropriate comfort model for MM buildings, many studies have investigated and made recommendations on the best approach. In [64], it was concluded that the adaptive model is applicable to MM buildings through an empirical study with questionnaires and temperature measurements on two MM buildings and one fully air-conditioned building in the southern of Spain. It was found that the PMV model overestimated the occupants' thermal sensation in the three case study buildings due to the adaptive opportunities in the buildings, which enabled the occupants to extend their comfort range. Thereby, it was concluded that the PMV model was not accurate for MM buildings. Similar conclusions were

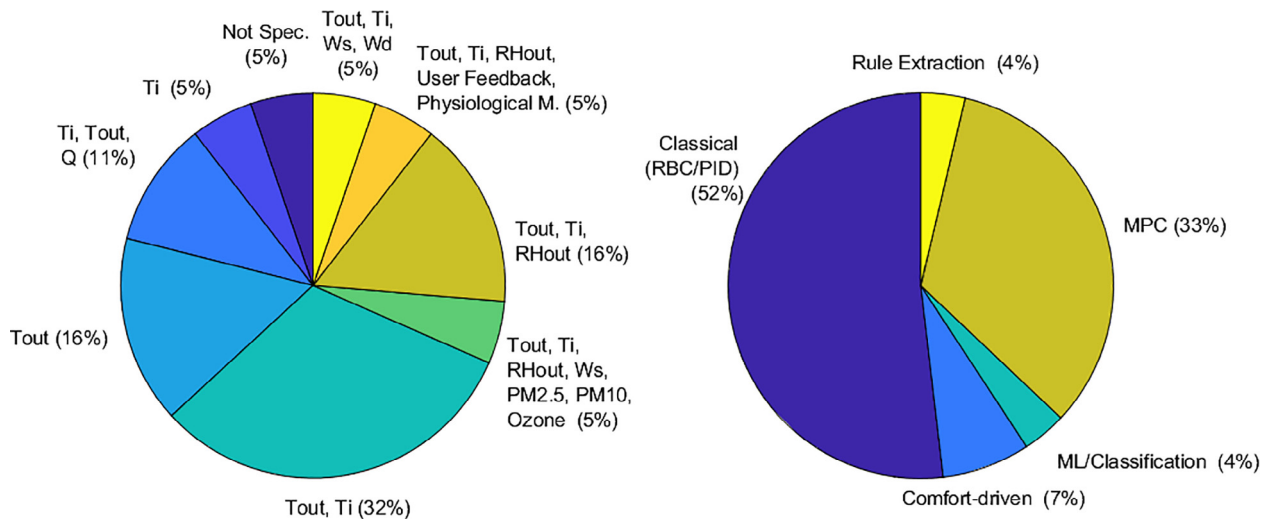


Fig. 12. Control Variables and Control Methods.

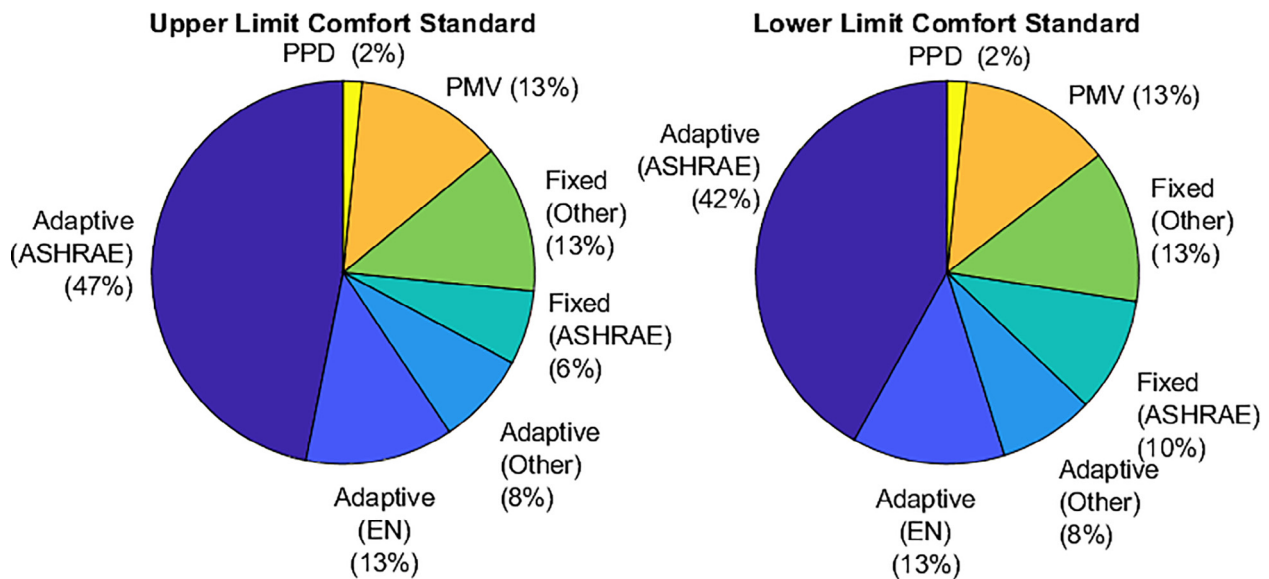


Fig. 13. Comfort standards used in the study.

reached in [68] regarding the suitability of the adaptive comfort standard for MM buildings. A longitudinal field study was conducted in an Australian mixed-mode office building to investigate how different modes of the building operation, i.e. air-conditioning and natural ventilation, impacted the perception of the occupants thermal comfort and the indoor thermal environmental. The findings showed larger degree of tolerance and adaptability of the occupants to indoor temperature changes during the NV operation than the AC operation. This translated into the thermal sensation vote of the occupants not conforming to the PMV values when the MM building was operating in NV mode. Rupp et al. [82] assessed the appropriateness of using a particular comfort model (i.e. ASHRAE Standard 55 and Givoni's method, [83]) for MM buildings located in hot and humid summer climate. Building performance simulations results were used to correlate the number of hours of air-conditioning use and the outdoor temperature and humidity. Givoni's method was found to be the most appropriate to assess hot and humid summer climates. Giovanni's method developed the thermal comfort zone in the psychrometric chart to account for the acclimatization and

comfort expectations of the occupants for buildings utilising passive cooling located in hot climates.

Considering the upper and lower limits of the comfort standards, it is seen that a fixed value for the lower limit is more common than a fixed upper boundary. MM buildings benefit more from the use of an adaptive upper boundary than an adaptive lower boundary, due to the use of ventilative cooling during the warmer periods. In [40], for example, a lower constant limit is imposed to the applicability of the adaptive model when analysing multiple MM cooling strategies. In [84], the number of hours where NV could be employed in a MM building was determined through a boundary layer meteorological model and the temperature thresholds following the adaptive ASHRAE model (upper limit) and a fixed temperature (lower boundary).

The least preferred comfort model to assess the thermal comfort on MM buildings is the predicted percentage dissatisfied (PPD). Only [85] used the PPD to control the ventilation of an institutional MM building in Montreal. It was found that the use of PPD could save up to five times more energy than the use of fixed boundaries for ventilation control. However, when a reactive type

of controller was used, it could lead to an uncomfortable environment.

As shown in Fig. 12, only a small number of papers consider only the indoor or outdoor temperature as a control variable (6% and 11% respectively) while the majority of papers use both indoor and outdoor temperature, either alone (33%) or in conjunction with other control variables (46%). Some of the papers, which focus their controllers on enhanced thermal comfort, include humidity within the comfort variables [56,62] as well as human physiological and behavioral factors, claimed to be important when implementing a human-focused HVAC control system [65].

Recent studies have also investigated the impact of including variables other than the ones affecting thermal comfort in the formulation of the control strategy and the consequent evaluation of the availability of natural ventilation. While natural ventilation is generally expected to provide significant energy savings, Chen et al. [45] found that the influence of outdoor air pollutants is typically neglected in the design and control development stages of a naturally ventilated building. They calculated that several cities in the US would be negatively affected if common outdoor air pollutants such as PM_{2.5}, PM₁₀ and ozone were considered as part of the control loop.

6.2. Control methods

Classical control methods most commonly used by the industry to manage MM buildings include Rule-Based Control (RBC) to manage high-level or supervisory decisions and PID controllers implement low-level control loops. The majority of the reviewed experimental research studies also adopt classical control techniques to manage their case study building [86,87]. This review also found that classical control methods were commonly adopted in those research studies where the impact of hybrid ventilation was investigated using simulations, including impact studies such as [45]. Whilst the majority of the papers reviewed used classical control as a control method either for the baseline benchmark or test case (52% of the cases used RBC and/or PID as shown in Fig. 12), more advanced control strategies such as Model Predictive Control have the potential to further improve the performance of MM buildings. Model Predictive Control (MPC) was the second most studied control method in the reviewed literature. This control framework has gained interest only relatively recently. MPC is a well-established method for constrained control and has been receiving extensive attention from researchers in the field of control of buildings in general. MPC merges principles of feedback control and numerical optimization, enabling the possibility of exploiting energy storage capabilities, including from the building fabric. This is achieved through the utilisation of predictions of future disturbances (e.g. internal gains, weather, etc.) as well as future requirements and constraints (e.g. comfort ranges) to anticipate the energy needs of the building, and thereby optimise its thermal behavior on the basis of the defined control goals. MPC uses these predictions to select the best sequence of future manipulated variables, according to a specific performance index. The latter is defined over a time window that starts from the current time and spans a given prediction horizon in the future. The best sequence is obtained by solving a numerical optimization problem, and only applies the first move of the optimal sequence at the current control time step. The process is repeated at each time-step, finding a new optimal sequence and applying again only the first element of the open loop optimal solution. This process is shown in Fig. 14, as presented in Serale et al. [88].

The MPC framework has been more widely implemented as modern optimization methods and increased processing power in buildings' control systems mean the high computational demand is less problematic. Despite this, most of the MPC studies reviewed

in this paper are only performed in simulation, with the exception of [89], where an MPC strategy was used to manage natural ventilation in a MM residential building. MPC approaches, incorporating knowledge of a systems dynamic behaviour and predictions of future disturbances, can fully exploit the night ventilation potential of an MM building. This was highlighted by Landsman et al. [46] in their study, which focused on night ventilation. They showed that an MPC approach could effectively utilise night ventilation to reduce discomfort degree hours for a building in a hot and humid climate which was not able to access day time ventilative cooling as much as in milder climates. The buildings dynamic behaviour was modelled using a grey-box approach, identifying parameters in a resistance-capacitance network. A similar approach was taken in [89], where the opening of the windows was modelled as a different resistance between the indoor and the outdoor spaces activated by a boolean variable. As modelling the heat and mass exchange processes involved in a natural ventilation process is complex and might be difficult in a large scale building, May-Ostendorp et al. [31] studied an MPC method in conjunction with a rule-extraction method to simplify its implementation. This was one of the first studies concerning MPC in MM buildings and was performed in 2011, while the other studies using MPC were published from 2014 onward. Results of simulation studies showed that MPC can significantly reduce the cooling requirements compared to a baseline controller by adapting the night setback control, while maintaining the operative temperature within acceptable limits during the occupied period [48,47]. Another study compared MPC with informed occupant manual controls that, while confirming a higher performance of the fully automatic natural ventilation control system with MPC, also showed that the informed occupant manual controls instructed by signals fail to show significant improvement compared to the spontaneous occupant control [56]. Other studies have used Neural Networks to model the buildings dynamics and optimise the operation of the MM building [62], while others presented predictive control strategies that, despite not meeting the requirements of an MPC framework, still highlight benefits when compared to baseline RBC controllers [85,59]. For simplicity, all these studies were categories under "MPC" in the summary data presented in Fig. 12. All studies that used a predictive approach to optimise the behaviour of a building had the main focus to exploit free cooling from ambient air. However, studies that explicitly focused on improving comfort used a different approach. In these cases a hybrid approach was utilised, employing classical control system with rules and set-points, but tuned using more advanced techniques. For example, the experimental study undertaken by Li et al. [65] utilised physiological data to better control the building using modern Machine Learning (ML) and classification methods to tune a classical controller, and demonstrated that human physiological and behavioral data can significantly improve the accuracy of predicting thermal preferences, and thereby identify the best control strategy. In [80] a simplified airflow network modelling was used to dynamically adjust the operation of a residential MM building to optimize for comfort objectives, also in this case relying on classical control approaches.

7. Discussion

This survey highlighted that, in the recent studies modelling the performance of MM buildings, the following features can be observed:

- There is an increasing trend in terms of paper published in this area, underlining that this area of research is still active and that hybrid ventilation is perceived as an effective measure to reduce buildings' energy consumption

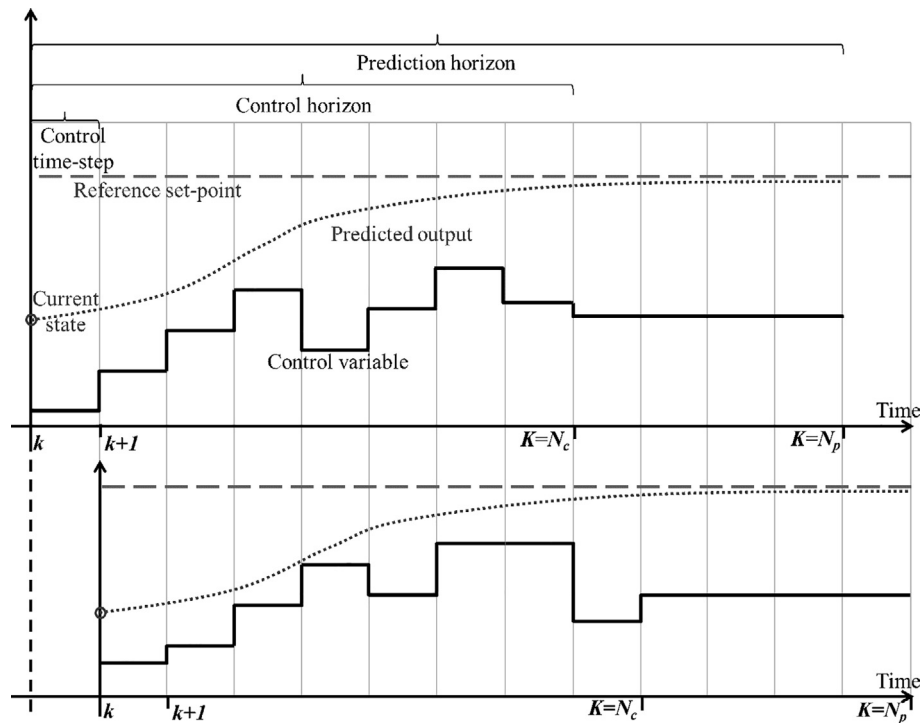


Fig. 14. Schematic of the principle of receding horizon, with the top and the bottom figure presenting operation at one time-step and the following one, as presented in [88].

- The more prevalent climates in which the studies were performed are Csa and Cfa (warm temperate climates with hot and dry or humid summers), followed by Csb and Csc climates (warm temperate, dry and warm or cool summers) and Bwh (Hot arid, dry winter), highlighting that the benefits from natural ventilation are sought not much where there is a large potential for climatic cooling (e.g. cold climates), but where the building have a significant need for cooling to maintain comfort conditions and the climate is mild enough to support a demand reduction.
- There is no consensus yet on which comfort standard should be used to assess a mixed-mode buildings. Nevertheless, the majority of the studies use the adaptive comfort theory, either from the ASHRAE or the EN standard, especially for the upper limit.
- Most of the studies reviewed in this survey were simulation studies. This is probably due to the difficulty of quantifying the benefits of having a MM building experimentally, as the same experiment cannot be identically repeated on the same building, with the same weather conditions. While performing a building performance simulation is therefore the most obvious solution to this problem, the large variability in terms of assumptions made in each simulation study makes their results difficult to compare with each other.
- The experimental studies showed that the majority of the studies assessed the effect of thermal comfort on MM buildings via monitoring campaigns. The experimental results reported that the adaptive comfort model is more relevant than the PMV-PPD for specific scenarios in MM buildings: such as when the building operates in NV, for a range of elevated outdoor temperatures, only when the windows operation are manual or semi automated, or for occupancy preferences.
- In terms of management of MM buildings, the studies surveyed are employing classical control methods, such as RBC and PID control, in the majority of the cases. This is probably due to the difficulty of applying more complex control methods to processes complex to model such as NV. Recent research studies

are focusing on predictive control methods, such as MPC, with the intent of better utilising the climatic cooling potential when cooling is not needed directly, by cooling the building fabric (e.g. better managing night purging).

- Most of the studies reviewed use indoor and outdoor temperatures to manage the operation of the building. While the majority of the other papers included other environmental variables to better manage energy and comfort (e.g. relative humidity, wind speed), some recent studies are also considering pollutants in the outdoor air as limiting factors to the possibility to use natural ventilation.

All the studies reviewed in this survey reported a potential building cooling demand reduction, which significantly varied, as expected, with climate, building type, and evaluation assumptions. The estimated cooling reduction ranged from 5% to 90% in the papers reviewed. The best estimate is probably to be identified in the climate locations where most of the studies were performed (Csa, Cfa, Csb and Csc) where on average the average potential cooling reductions reported were between 20% and 45%. From a controls perspective, recent research in testing and implementing predictive control strategies has highlighted the potential energy savings that exists in the management of natural ventilation systems to more effectively exploit thermal mass and better match comfort requirements. However, it is challenging to implement a controller that can effectively exploit this potential. The availability of free cooling varies dynamically according to ambient and building temperatures, and the possibility to exchange air is driven by varying wind conditions. Most of the model-based approaches require a model of the building, and a model of the air flow within it to estimate the effect of window opening on the thermal response of the building. This is challenging as each building is unique. For this reason different white, grey and black box modelling techniques have been studied to attempt to identify optimal control sequences. White-box modelling approaches are more accurate in describing the physics of the system, but generally

not directly suitable for real-time optimization, while black-box models, whilst simple and data-driven, do not retain the insights of the physical phenomena driving the thermal processes in the buildings. Grey-box modelling is a compromise between these two approaches, however in the studies evaluated it typically required a simplification of the physical processes involved. Comfort was also considered an important performance indicator to be optimised in this category of buildings, and unconventional feedback methods such as smart fitness and health monitoring devices wristbands were used to collect data for the control system to be used. Some of the studies surveyed also highlighted the importance of MM buildings in the future, as they have simulated buildings with various energy efficiency features using future climates, and have indicated hybrid ventilation as one of the most impactful measures to alleviate the increase in cooling demand as the climate becomes warmer. The implementation of MM ventilation can thereby be an essential avenue towards a more sustainable built environment to mitigate climate change and reduce our carbon footprint.

Future research directions should investigate how to effectively integrate and manage hybrid ventilation incorporating scalable optimal control methods and additional control parameters, such as air pollutants. In addition, novel avenues should explore methods to capture feedback directly from the user (e.g. user in the loop) to exploit the full potential of MM buildings to achieve thermal comfort and energy targets. The pressing need to mitigate the impacts of climate change is an imperative to improve the resilience of our buildings for future climates, thereby studies evaluating the effect of future climate predictions for MM buildings on social, environmental and financial indicators should be conducted.

8. Conclusions

This survey critically assessed the research papers published in the past 10 years with the objective of estimating the cooling energy reduction potential of MM buildings and the proposed building management solutions to exploit as much as possible the benefit of the outdoor air conditions. This article found that MM buildings have increasingly been investigated in recent years due to the critical role the buildings can play in improving the energy efficiency of our built environment. Warm temperate climates have been shown to be the most appropriate for hybrid ventilation due to good alignment between a buildings cooling needs and the mildness of the climate. The majority of the reviewed studies were undertaken via simulation tools due to the simplicity of investigating multiple scenarios and controlling inputs, when compared to experimental studies. The downside of the simulation studies was found to be the diversity of the input assumptions, making the results difficult to compare with each other. Additionally, the reviewed papers have revealed that there is no universal thermal comfort standard for MM buildings, but that the adaptive thermal comfort theory is the most widely used. The analysis of the studies on methods for control of hybrid ventilation system found that well-managed systems is key to an effective MM building operation. This management is typically undertaken with classical control methods, probably because they require less effort to implement than more sophisticated control techniques. However, the review has highlighted the importance of coordination between systems to ensure operational effectiveness.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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