PERFORMANCE EVALUATION OF MIXED-MODE VENTILATION WITH AN OPTIMAL CONTROL

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ABSTRACT
This study presents the assessment of a mixed-mode (MM) ventilation system with an optimal control to improve energy consumption and thermal comfort levels in a residential building located in Brighton, UK. An energy model was built via EnergyPlus and used to develop an optimal control with the Genetic Algorithm as an optimiser. When compared to conventional MM operations, it was found that a better control over indoor thermal conditions as well as reduced energy loads were achieved with the application of the optimal control. It was also demonstrated that enhanced existing building design features, such as increased thermal mass, could facilitate and highly improve the operation of MM ventilation, especially when an optimal control was considered.

INTRODUCTION
Households are responsible for more than a quarter of energy use and carbon emissions in the UK (Palmer et al. 2013). Improving the energy-efficiency of housing has therefore become increasingly important. The particular focus of this study is the operation of “Mixed-mode” buildings, which adopts a combination of natural ventilation and mechanical ventilation/cooling for space conditioning. An environmental-friendly MM building is expected to minimise energy consumption without compromising indoor air quality and occupant thermal comfort. This requires a control system that is able to operate and switch between natural ventilation and mechanical ventilation/cooling in response to the variations of indoor and outdoor weather conditions. Ideally, natural ventilation is used as a primary mean of providing cooling and, when this is not possible, active cooling is introduced. In this way, MM ventilation can scale back or eliminate the use of mechanical systems and thereby help reduce the operating cost of year-round air conditioning.

Existing Mixed-mode Controls
In Europe, design guidelines for MM ventilation have not yet been codified by any standard protocols, nor is there consensus in regards to MM controls. Current practices normally involve a series of heuristic controls, such as if the outdoor temperature drops below 25 °C, mechanical systems are switched off and windows are opened, some of which have been shown to offer a satisfactory indoor thermal condition, but mostly at a significant operating cost. Given their simplicity and heuristic nature, those strategies show no evidence of an effective respond to the variations of indoor and outdoor weather conditions, or modifications in some existing building design features, such as increased thermal mass (Brager et al. 2009). Besides, most MM buildings are not fully automated, and occupants usually have to control their windows, fans and air-conditioning based upon common sense and experience. This approach could result in thermal discomfort and energy waste since it is difficult for occupants to operate the MM ventilation system in a reasonable and energy-efficient manner all the time. For instance, sometimes they can overcool or overheat the space due to a lack of ability to tell whether the indoor-to-outdoor temperature difference is suitable for the window to remain open or closed.

Objective
The objective of this study is to assess the impacts upon energy consumption and thermal comfort levels of an optimal control designed and proposed for a MM building (natural ventilation + mechanical ventilation + solar shading).

Building Description
The building studied is sited in Brighton, UK and was designed and built (2008-10) considering the One Planet Living principles and to be Zero Carbon through a combination of good thermal design and on- and off-site renewable generation technologies. Sufficient cooling to minimise the risk of overheating in summer is provided through the use of a combination of the fan assisted ventilation system and exposed thermal mass. Nevertheless, a Post Occupancy Evaluation carried out in the building has shown some degree of overheating from both monitored environmental conditions and occupants’ satisfaction surveys (Altamirano-Medina et al. 2014). Exact reasons of the monitored overheating are not fully understood but could be down to occupant behaviour. Differences in overheating rates among the monitored apartments imply that occupants might adopt different cooling strategies with respect to windows, fans and shading devices. As the risk of overheating is likely to increase with rises in seasonal
atmospheric temperature resulting from climate change, useful measures to deal with summer discomfort and overheating issues should be proposed.

SIMULATION

As shown in Figure 1, the living room of one of the apartments of the building was modelled. It has one exposed wall facing east, one interior wall connected to the corridor as well as two separate partitions. Cooling is provided by natural ventilation via a sliding balcony window that is adjusted by the occupant and mechanical ventilation via a fan-assisted ventilation system. The balcony window is equipped with an internal curtain for protection against solar radiation (Figure 2). This living room is occupied by an adult from 7:00 to 23:00 each day. Details on building constructions and system configurations are presented in Table 1.

Table 1 Building characteristics

<table>
<thead>
<tr>
<th>Fenestration &amp; Shading</th>
<th>Insulation</th>
<th>Airtightness</th>
<th>Internal Gains</th>
</tr>
</thead>
<tbody>
<tr>
<td>Triple glazing: U=0.8W/m²K, SC=0.82, glazed area=4.5m², and the balcony window has an overhang of depth 0.5m, 0.2m above.</td>
<td>External wall: U=0.21W/m²K</td>
<td>Background infiltration=0.25ACH</td>
<td>Lighting: 8W/m², machines: 8W/m² (S/L=1.6), and one person: 130W (S/L=1.4).</td>
</tr>
</tbody>
</table>

[1] SC = shading coefficient
[2] S/L = sensible heat / latent heat

The thermal dynamics of the model were predicted using EnergyPlus (version 8.1.0.009). The airflow inside the building, including flows caused by windows, fabric leakage and mechanical forces, was computed through EnergyPlus’s airflow network module. Data on wind pressure coefficients were estimated from the generalised data set provided by CIBSE AM10 (CIBSE 1997). Two cases were considered in this study, namely the base and optimal cases. The base case shows the ways in which occupants normally operate their windows and fans for cooling purposes, whilst the optimal case manifests the operation of MM ventilation programmed by the optimal control.

Assumptions

Window opening: Windows of the base case were manually operated by occupants. The Humphreys algorithm developed by Rijal et al. (2008) showed that the possibility of windows open can be governed by a logistic regression curve (Equation 1) using indoor operative (\(T_{io}\)) and outdoor air (\(T_{oa}\)) temperatures as the deciding factors. Windows are opened at their full effective opening areas when the possibility factor (\(P_o\)) is greater than the threshold of 0.5 and vice versa. This algorithm has been shown to adequately predict the patterns of window opening in some MM buildings, and was therefore adopted in this study. As for the optimal case, it was assumed that windows could be opened and closed at any time by following the orders of the optimal control (which normally needs the assistance of actuators but is ignored in the current study).

\[
\log \left\{ \frac{P_o}{1-P_o} \right\} = 0.171T_{io} + 0.166T_{oa} - 6.4 \tag{1}
\]

Window operation: The window is composed of two parts, one is the opening through which air exchanges freely take place and the other is the window closed with no airflow permitted. A heavy solid curtain behind the window is used during the day as a shading device to protect against solar gains. Hence, there is the possibility that the curtain could restrict airflow when the window is in an open position. In practice, the particular amounts of air blocked by the curtain depend upon many factors, such as curtain type, material and wind speed. In order to avoid this uncertainty, it was assumed that the curtain would only apply to the part of the window that remained closed so that airflow through the opening was not affected (Figure 2).
Control Decisions

In this study, control decisions were defined regarding the opening ratio (the ratio of opening area to total window area), the fan speed and the curtain ratio (the ratio of curtain area to total window area). As the objective of the optimal control is to minimise energy consumption while still maintaining occupant thermal comfort, the control problem can be mathematically formulated as:

Minimise: \( E_{\text{total}} = E_{\text{fan}} = f(x, y, z) \)
Subject to: \( x \in \{0, 0.25, 0.5, 0.75, 1\} \)
\( y \in \{0, 0.25, 0.5, 0.75, 1\} \)
\( z = 1 - x, \) from 05:00 to 19:00 and
\( = 0, \) from 19:00 to 05:00 (2)

where \( E_{\text{total}} \) is the total energy consumption, which is equal to the fan energy use. Decisions in \( x, y \) and \( z \) refer to the opening ratio, the fan speed (l/s) and the curtain ratio, respectively. Five values that represent typical window positions (0, 25%, 50%, 75% and 100% of the window area in an open position) were selected. The fan was designed to operate at four different speeds: 'off' - 0, 'trickles' - 7.1 l/s, 'medium' - 14.2 l/s and 'boost' - 17.8 l/s. Part of the window in a closed position was covered with a curtain during the day (05:00 - 19:00) and remained uncovered at night (19:00 - 05:00).

Optimal decisions \( (x, y, z) \) leading to a minimum energy cost were adopted. Meanwhile, they must be subject to the following requirements:
- Temperature: during the occupied hours, indoor air temperatures were allowed to fluctuate within the comfort band determined by the ASHRAE 55 (ASHRAE 2014) adaptive model of 80% acceptability.
  Upper limit (\(^{\circ}\)C) = 0.31 \( \bar{t}_{\text{pma(out)}} \) + 21.3
  Lower limit (\(^{\circ}\)C) = 0.31 \( \bar{t}_{\text{pma(out)}} \) + 14.3 (3)
  where \( \bar{t}_{\text{pma(out)}} \) is the running mean outdoor air temperature
- Overheating: indoor air temperatures should comply with, at the very least, two of the three CIBSE overheating criteria to minimise the risk of overheating. Details of how these criteria are calculated can be found in TM 52 (CIBSE 2013).
  1: Hours of Exceedance \( (H_e) \) \( \leq 3\% \)
  2: Daily Weighted Exceedance \( (W_e) \) \( \leq 6 \) Kh
  3: Upper Limit Temperature \( (T_{\text{upp}}) \) \( \leq 4 \) K (4)
  - Fresh air: a minimum of 10 l/s \( \cdot \) person was required to maintain good indoor air quality (CIBSE 2006), in which case mechanical ventilation must be switched on if the provision of fresh air through natural ventilation was insufficient.

Control Time-horizon

The control problem was formulated over a 24-hour time-horizon, which was then segmented into 1-hour-long blocks of time for control decisions to be made. Present decisions are a function of past decisions due to the thermal storage effect of thermal mass. It is therefore necessary to take a warming-up period to pre-condition the building. As suggested by May-Ostendorp et al. (2013), a period of two days is sufficient for pre-conditioning purposes. The chosen receding time-horizon is illustrated in Figure 3, where past control decisions (Day One & Day Two) establish the thermal history of the building and therefore affect the control decisions made in the current timeslot (Day Three).

Optimisation Process

A search heuristic named Genetic Algorithm (GA) was used to find optimal control decisions. The diagram schematic of the optimisation environment is shown in Figure 4, demonstrating the adopted approach. In a single generation, GA (embedded in jEnergyPlus+EA) generates an idf file containing the proposed control decisions and passes it to EnergyPlus for simulation, whose csv results are then read back to GA to decide how to proceed to the next generation of the idf file. This process continues until a plateau has been reached such that successive iterations no longer produce better results (i.e. the minimum energy use).

Figure 3 Procession of receding time-horizon using one-hour time blocks to find optimal control decisions

Figure 4 The optimisation environment, coupling EnergyPlus and GA
DISCUSSION AND RESULT ANALYSIS

The simulation results were subject to two running periods of three consecutive days, representing mild and hot summer outdoor conditions (mean-max-min = 23.2: 29.4: 13.9 °C, and 25.9: 33.4: 19.6 °C, respectively). As suggested by the CIBSE (2013), the current weather data used to assess summer building performance were derived from the Design Summer Year (DSY), which contains the third highest average temperature of the periods April-September over a set of 20 years. The first two days were not included in the analysis as they were treated as a ‘warmup’ period, during which the solution pattern started to establish itself. All of the optimal control results were compared to a base case that depicted typical MM configurations by incorporating the Humphreys algorithm and heuristic rules specified in Table 2.

Table 2 Heuristic rules used in the base case

<table>
<thead>
<tr>
<th>Rule Num.</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>Run the fan at trickle speed to provide fresh air when necessary.</td>
</tr>
<tr>
<td>(2)</td>
<td>Use the curtain to protect against solar gains once the windows total transmitted solar radiation rate exceeds 500 W/m².</td>
</tr>
</tbody>
</table>

[1] Refer to Zhai’s filed studies (2011) of MM buildings

Mixed-mode ventilation on a mild summer day

When using GA to find optimal control decisions, the convergence of results needs to be identified first since not all the options have been checked. The optimisations using 100, 200, 300, 400 and 500 generations with a population size of 20 are presented in a scatter plot (Figure 5). It can be seen that after 400 generations the solution dots virtually overlap one another, leading to a satisfactory convergence. Then, optimal decisions were found based on the criterion that no indoor operative temperatures exceeds the temperature comfort band at the expense of minimum fan energy costs.

One of the optimal solutions is shown in Figure 6, in which the base case has been included for comparison purposes. The room operative temperatures and energy requirements are illustrated in Figure 6a-b, in conjunction with window opening and curtain patterns presented in Figure 6c-d. Comfort limits are applied to the occupied hours as highlighted by dotted lines. As for the optimal case, all the operative temperatures fall within the comfort band, and therefore no cooling loads (Figure 6a-b). In contrast, the base case demonstrates a much higher uncomfortable percentage (62.5%) of occupied hours exceeding the threshold temperatures, thereby requiring a cooling load of 1.58 kWh to keep indoor temperatures below the upper comfort limit during occupied hours. The assessment of overheating risk using the three CIBSE criteria is shown in Table 3. It is seen that the optimal case is free from overheating with all the three criteria fulfilled, whilst the base case fails two criteria and is therefore classed as overheating. As shown in Figure 6b, the energy requirements of the base and optimal cases are presented in positive and negative patterns, respectively. Hence, their sum shows the variation of the cumulative energy saving (which is 2.5 kWh at the end of the day) achieved by the optimal control. The following two subsections explain in detail the ways in which the optimal control is able to produce these thermal comfort and energy benefits.

- **Impacts of window opening and curtain patterns**

One of the most common ways to get rid of excessive heat is to open the window to enhance heat transfer between indoor and outdoor environment. This practice is in line with the window opening pattern found in the base case. Figure 6c shows that the window is fully open throughout the day with the exception of times (11:00 to 13:00) when the transmitted solar radiation exceeds 500 W/m² so that the curtain is used as protection from solar gains (Figure 6d). However, as shown in Figure 6a, room operative temperatures of the base case exceed the upper comfort limit during the occupied hours from 10:30 to 20:30. This could be down to two reasons: first, inappropriate window opening behaviours, such as that the window is fully open even when air temperatures outside the building are higher than inside between 14:00 to 19: 00 (Figure 6a & c), and second, solar shading only lasts for two hours (11:00 to 13:00, Figure 6d), which may not be enough to offset solar gains received during the day. In practice occupants usually decide whether to open windows or use curtains based upon intuition and therefore do not necessarily know how to identify outdoor climate conditions, hence when to open windows to let in cold outdoor air or use curtains to prevent excessive solar gains.

The optimal case, on the contrary, receives its comfort and energy benefits from operating and switching between natural/mechanical ventilation and solar shading in response to the variations of...
indoor and outdoor weather conditions. For example, Figure 6c shows that the window is closed between 11:00 to 20:00 so as to avoid the mixing of warm entering air with colder inside air, and in the meantime the curtain is used to protect against solar gains (Figure 6d). But of course, shutting the window requires the fan operated at trickle speed to provide background ventilation and maintain indoor air quality (11:00 to 20:00, Figure 6b). Moreover, the window is partially open and coordinated with the curtain in the morning (06:00 to 11:00, Figure 6c-d) to protect against low-level sun while still conserving the cooling potential of cold outdoor air.

- **Impacts of night cooling management**

Another critical characteristic of the optimal case is its night cooling management. Given that occupants do not tend to adjust windows when they are asleep, the window position at night was therefore assumed to be the same as it was at the end of the occupied period (i.e. 23:00).

The base and optimal cases are demonstrative of quite different temperature profiles at the end of the night (04:00 to 06:00, Figure 6a). The focus may move towards the operation of the fan, whose function is to force cold outdoor air into the room to flush the heat stored in the building fabric. On the one hand, the fan of the base case is inactive as relevant heuristic control rules are unavailable at this stage. On the other hand, the optimal case switches on the fan at boost speed during the period from 04:00 to 06:00 (Figure 6b). Regarding this observation, the question may arise: why to use the fan at this specific time? One may consider the temperature trajectories depicted in Figure 7 that shows the impacts upon room operative temperatures of running the fan at different times of the night for an operation lasting two hours. All the control settings remain the same except for the scheduled starting time of the fan.

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Value/Satisfy?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base case</td>
<td>Optimal case</td>
</tr>
<tr>
<td>(1) ( H_e )</td>
<td>31%/No</td>
</tr>
<tr>
<td>(2) ( W_e )</td>
<td>10/No</td>
</tr>
<tr>
<td>(3) ( T_{upp} )</td>
<td>2/Yes</td>
</tr>
</tbody>
</table>

It is noted that during occupied hours, the room operative temperatures can fall within the comfort band, but only with the operation of the fan started at 04:00. Looking at the outdoor air temperature profile during that running period (04:00 to 06:00), it becomes apparent that the appropriate time to use the fan is when the outdoor air temperature approaches its relatively low values. This pre-cooling strategy, however, could have a negative effect on some occasions and thereby lead to overcooling at the outset of occupancy. For example, although running the fan from 05:00 to 07:00 can help to achieve lower daytime temperatures compared to running it from 04:00 to 06:00, this is not feasible as part of the morning suffers from overcooling (07:00 to 07:20 when indoor temperatures drop below the lower comfort limit). These findings are somewhat similar to Spindler’s study (2004), which pointed out that if the running time is limited, the fan should be in operation at the final segment of the night-time period when outdoor air is cold enough for night cooling purposes.

*Figure 6 Simulation results of a) indoor operative temperatures, b) energy requirements and saving, c) opening ratios and d) curtain ratios for the base and optimal cases on a mild summer day*
The impacts on room operative temperatures of running the fan at different times of the night for an operation lasting two hours.

Mixed-mode ventilation on a hot summer day

Again, the results of optimisation using 100, 200, 300, 400 and 500 generations were tested (Figure 8). It is seen that after 300 generations the solution dots virtually overlap one another, leading to a satisfactory convergence. However, this time the optimal solutions surprisingly have 78% of occupied hours outside the comfort band. A group of optimal solutions were randomly selected with their operative temperature trajectories presented in Figure 9. Although the selected solutions deliver the same comfort level, their temperature profiles can differ greatly from one another. This observation implies that the degrees of the severity of overheating among the optimal solutions could be different. As such, the one comprising the minimum degrees above the upper comfort limit was adopted as the optimal case. Figure 10 shows the results of operative temperatures, energy requirements and saving, opening ratios and curtain ratios for both cases. The optimal case outperforms the base case in terms of the comfort percentage, 22% versus 12% (Figure 10a). In addition, the cumulative energy saving achieved by the optimal control is up to 8.7 kWh at the end of the day (Figure 10b). The assessment of overheating risk (Table 4) indicates that both cases suffer from overheating: the base case fails all of the three criteria and the optimal case fails the first two criteria. For one thing, the ability of the optimal control to effectively operate natural/mechanical ventilation and solar shading still contributes to its energy performance and thermal comfort levels. Nevertheless, night cooling management does not seem to be an obvious advantage for the optimal case anymore as its temperature profile at night is somewhat similar to that of the base case (Figure 10a). This is not a surprising result due in part to the fact that outdoor air temperatures are way too high during the day and not cold enough at night, which can greatly lessen the cooling capacities of natural ventilation even with the assistance of fans.

Up till now it has been found that on a hot summer day, the performance of MM ventilation in terms of minimising energy consumption and preserving thermal comfort can be improved by the optimal control to some degree, but is not in line with the expectation of 100% comfort levels and no overheating issues. This could be down to two reasons: first, as discussed before, high external temperatures significantly reduce the cooling capacities of natural and fan assisted ventilation, and second, some building design features (e.g. thermal mass) that are supposed to facilitate MM ventilation have not been utilised to their fullest.

It turns out that unfavourable weather conditions are inevitable so the focus may move towards the building design features, such as thermal mass. The following subsection will investigate the impacts of increased thermal mass upon the decisions made by the optimal control and ultimately the performance of MM ventilation.
• **Impacts of increased thermal mass**

Heavy constructions were used to provide additional thermal mass to the existing lightweight floor, ceiling and party walls. The thermal properties of building fabric before and after the addition of thermal mass are tabulated in Table 5. Simulation results are presented in Figure 11. It can been seen that the fluctuation of operative temperature is greatly attenuated, where the peak value drops by 1.7 °C (Figure 11a). In addition, after increasing even more thermal mass, all the occupied hours fall within the comfort band and the cumulative energy saving at the end of the day reaches 2.0 kWh (Figure 11b).

Regarding the optimal control, a significant difference is observed in the use of the fan. Figure 11c indicates that the fan is operated at a higher speed at night to flush the heat stored in the building fabric. This is mainly attributed to more heat absorbed by thermal mass in the daytime. In a conclusion, MM ventilation can benefit from the addition of thermal mass, and the optimal control is able to capture this benefit.

| Table 4 Assessment of overheating risk according to three CIBSE criteria on a hot summer day |
|---------------------------------|-----------------|-----------------|
| Criterion                      | Base case       | Optimal case    |
| (1) $H_4$                      | 46%/No          | 31/No           |
| (2) $W_e$                      | 43/No           | 11/No           |
| (3) $T_{upp}$                  | 5/No            | 0/Yes           |

| Table 5 Fabric properties before and after the addition of thermal mass$^{[1]}$ |
|-------------------------------------|-----------------|-----------------|
| Floor/Ceiling                       | Before | After | Before | After |
| Thickness (m)                       | 0.1    | 0.1   | 0.3    | 0.3   |
| Density (kg/m$^3$)                  | 1300   | 2500  | 1500   | 2800  |
| Specific heat (kJ/K·kg)             | 0.7    | 1.0   | 1.0    | 1.6   |
| Conductivity (W/m·K)               | 1.68   | 1.66  | 1.71   | 1.75  |
| Thermal capacity (Wh/K·m$^2$)      | 35     | 68    | 37     | 79    |

$^{[1]}$ Refer to CIBSE Guide A (CIBSE 2006)

CONCLUSION

This study presents the assessment of MM ventilation incorporating an optimal control in a MM building sited in Brighton, UK. The optimal control is aimed at minimising energy consumption for mechanical conditioning while still maintaining indoor operative temperature at an acceptable level. Simulations were conducted over two periods that represented mild and hot summer conditions, and the comfort and energy performance attributed to the implementation of the optimal control (optimal case) was compared against a typical MM ventilation configuration (base case).

Based upon the results, the following conclusions can be drawn:

• On a mild summer day, the optimal case consistently outperformed the base case. Its room operative temperature profile fell within the comfort band, whilst the base case only led to 37.5% of occupied hours adhering to this band and was also classed as overheating in light of the three CIBSE overheating criteria. Besides, the optimal case achieved an energy saving of 2.5 kWh, by virtue of operating and switching between natural/mechanical ventilation and solar shading in response to the variations of indoor and outdoor weather conditions, as well as effective night cooling management.
throughout the day and 2) building design features that could facilitate MM ventilation had not been utilised to their fullest.

- A modified building model incorporating higher thermal mass resulted in less energy consumption and better comfort levels. It was seen that the optimal control effectively responded to this change by operating the fan at a higher speed at night to sufficiently remove the increased amount of heat stored in the building fabric.

![Simulation results of a) indoor operative temperatures, b) energy requirements and saving, c) opening ratios, d) curtain ratios for the optimal case with and without increased thermal mass on a hot summer day](image)

**REFERENCES**


**NOMENCLATURE**

- \( U \): overall heat transfer coefficient, W/m\(^2\)K;
- \( T_{\text{int}} \): indoor operative temperature, °C;
- \( T_{\text{out}} \): outdoor air temperature, °C;
- \( P_w \): possibility factor of window open;
- \( E_{\text{total}} \): total energy consumption, kWh;
- \( E_{\text{cooling}} \): cooling energy, kWh;
- \( E_{\text{fan}} \): fan energy, kWh;
- \( T_{\text{pm}}(\text{out}) \): running mean outdoor air temperature, °C;
- \( H_e \): hours of exceedance, %;
- \( W_e \): daily weighted exceedance, kh;
- \( T_{\text{upp}} \): upper limit temperature, K;
- \( E_{\text{fan}} \): fan energy, kWh.