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Published in:
IOP Conference Series: Materials Science and Engineering

DOI (link to publication from Publisher):
10.1088/1757-899X/609/3/032013

Publication date:
2019

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Guo, R., Hu, Y., Liu, M., & Heiselberg, P. (2019). Optimal night mechanical Ventilation control strategy in office buildings. *IOP Conference Series: Materials Science and Engineering*, *609*(3), [032013]. https://doi.org/10.1088/1757-899X/609/3/032013

IOP Conference Series: Materials Science and Engineering

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To cite this article: Rui Guo *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **609** 032013

IOP Conf. Series: Materials Science and Engineering **609** (2019) 032013 doi:10.1088/1757-899X/609/3/032013

Optimal Night Mechanical Ventilation control strategy in office buildings

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Abstract. Overheating in buildings during summertime, especially in office buildings is emerging as a challenge. Night mechanical ventilation (NMV) seems to be an energy-efficient technique by inducing the cold ambient air with a fan to cool the exposed building thermal mass and save air-conditioner energy for the following day. However, as sufficient cooling energy should be stored in thermal mass at night, the minimum indoor air temperature setpoint is relatively low, which may cause an overcooling penalty. Moreover, the NMV energy consumption may outweigh the energy saved for the air-conditioner at next daytime. Therefore, a multi-objective optimization was conducted to explore the optimal NMV control strategy to improve the building energy performance and indoor thermal comfort concurrently, based on a typical office building with three thermal mass levels in three climate regions. The final optimal NMV control strategies under different scenarios are presented in this study. The results show that the total cooling energy consumption of the final optimal NMV control strategies reduces 0%-8.6%, while the Predicted Percentage of Dissatisfied (PPD) during occupied hours decreases 0%-59.4%, compared to the base NMV control strategy in different scenarios. The benefit of the night cooling control strategy optimization is obvious in cold and medium climate region.

1. Introduction

An appropriate designed night mechanical ventilation (NMV) can enhance the night cooling efficiency significantly [1]. Several researchers have studied efficient NMV control strategies. Kolokotroni et al. [2] simulated an air-conditioned office building with night cooling and prescribed the night cooling operates continuously at night until 7:00 am when the inside and outside temperatures exceed 18 and 12 °C, respectively. Several NMV strategies were compared by simulations with EnergyPlus in a typical air-conditioned office building in northern China. The results show that the efficiency of NMV is improved when the operation time is close to active cooling time and the NMV duration is long [3]. A typical office building in Adelaide was simulated with several NMV setpoint temperatures and air change rates. The results show that the most energy-saving case is achieved with the night setpoint temperature of 15 °C and air change rate of 12 h^{-1} [4]. Wu et al. [5] studied a night ventilation coupled with active cooling (NVCAC) system for large supermarkets in cold climates, indicating that the night ventilation should be opened after the active cooling is closed. Vidrih et al. [6] examined a generalized model-based predictive weather control (G-MPWC) algorithm to control the air flow rate of NMV by reducing the building energy demand and found it seems to be effective.

The aforementioned NMV control strategy only focused on several control strategy parameters or just evaluated by a single indicator in one building or in one climate region. To get an optimum NMV control strategy, research should include various indicators and take the building configuration and climate into consideration. This paper selects the *total cooling energy consumption* and *PPD during occupied hours* as objectives for multi-objective optimization to investigate the optimal NMV control strategy in a conditioned office building. The design parameters of the NMV control strategy includes air change rate (ACH), minimum indoor temperature setpoint, night cooling duration, and threshold temperature (i.e., the temperature difference between indoor and ambient air for activation). Then the final optimal NMV control strategy for each scenario is obtained by a simple decision-making method. Finally, the values of two objectives of the final optimal NMV control strategy and the base NMV control strategy are compared to evaluate the optimization benefit in different scenarios.

2. Methodology

2.1. Building model

A building model built by EnergyPlus originated from an office building located in Aarhus, Denmark, as shown in figure 1 (A). The building is 103.7 m long and 9.5 m wide, with 3 stories and a total area of 2924.1 m^2. The layout of the office building can be seen in figure 1 (B). A typical office room 1W occupied by 6 persons was selected as the case room. The room floor area is 51.3 m^2, with 2.8 m height. The windows in room 1W are the energy-efficient windows with a double pane construction made of 3mm glass and a 13mm argon gap. Internal partitions between the concerned zone 1W and adjacent zones are set as adiabatic by assuming the similar conditions in all adjacent zones.

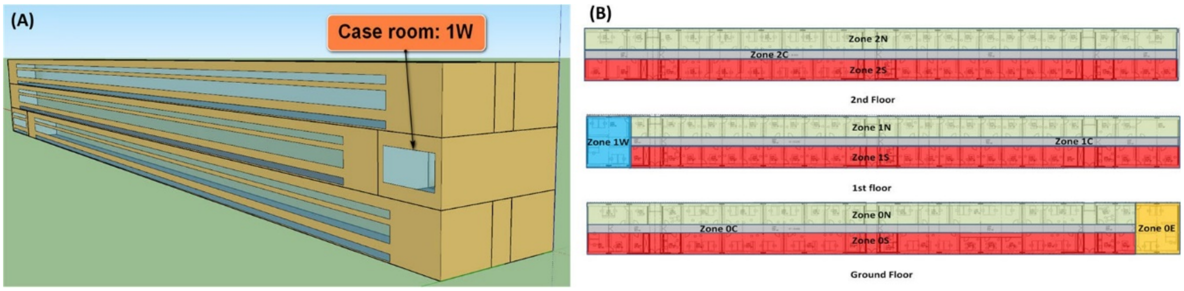


Figure 1. (A) View of the model and the case room (B) Layout of the case office building.

The internal heat gains are set as people with 120 W/person, lights with 6 W/m^2, electric equipment with 8 W/m^2. The hourly operational schedules for internal heat gains are always 1.0 during the occupied hours (08:00-17:00) and 0 for the other hours. The infiltration of building airtightness was set as 0.5 h^{-1} [7]. According to EN 15251, the people clothing insulation is set 0.5 clo in summer [8]. A packaged terminal air conditioner (AC) with COP 3.2 and setpoint 24.5 ℃ for cooling from the HVAC Template module of EnergyPlus is equipped in the zone 1W [8]. The outdoor air flow rate is set as 30 $m^3/(h\cdot person)$ and a factor 1.2 is used for sizing HVAC. The AC operating period is 08:00-17:00 on weekdays from 1st June to 1st October. The NMV system is a balanced system with a supply fan and an exhaust fan. The total design pressure is 600 pa, and the fan total efficiency is 0.9, whose total specific fan power (SFP) fulfills the recommended 'good-practice' from the technical note AIVC 65 [9].

Three different constructions of the external wall, internal wall, ceiling, floor, and internal mass are defined as light, medium and heavy thermal mass level, to investigate the influence of thermal mass on NMV control strategy. The dynamic heat capacity per unit floor c_{dyn} calculated by EN ISO 13786 [10] determines the thermal mass level when the building component is exposed to a sinusoidal temperature variation for a period of 24 h with surface resistance. For the light, medium, heavy thermal mass level, the c_{dyn} are 77.2 kJ/ $(m^2\cdot K)$, 182.5 kJ/ $(m^2\cdot K)$, and 231.1 kJ/ $(m^2\cdot K)$, respectively.

The case room is simulated in three different representative climates: Rome (hot), Geneva (medium) and Copenhagen (cold) to investigate the climate impact on the NMV control strategy optimization. The weather data for the three locations originate from the World Meteorological Organization [11].

2.2. Multi-objective optimization

To investigate the optimal NMV control strategy, a multi-objective optimization is conducted by the software jEPlus+EA [12]. The jEPlus+EA couples with parametric simulation manger jEPlus alongside the simulation engine EnergyPlus to conduct the multi-objective optimization by a common-used Non-dominated Sorting Genetic Algorithm II (NSGA-II) [13]. The *total cooling energy consumption* (i.e., AC+night ventilation fans energy consumption) and the *PPD during occupied hours* are two objectives to be minimized simultaneously. The evolution of the population continues as long as at least one of the stop criteria is satisfied. The population size, maximum generation number, crossover number, mutation number, and tournament selector size are set as 10, 200, 1.0, 0.2, and 2, respectively by compromising the computational cost and the accuracy of the Pareto front solutions.

Since the maximum ACH for night ventilation should not exceed 10 h^{-1} [14], the design ACH for night mechanical ventilation is set from 0 to 10 h^{-1}. Furthermore, to prevent the draught problem and to store more cooling energy in the thermal mass, the minimum indoor air temperature setpoint for night cooling should not less than 18 °C [15]. Therefore, this paper selects 18 °C, 19 °C and 20 °C as variables for the minimum indoor air temperature setpoint. The night venting schedule is between 17:00 and 08:00 (+1) from 1st July to 1st October, except for Saturday. 120 combinations in total with 1 h interval was set as the variables for night ventilation duration. The threshold temperature for night cooling activation was set as 1 °C, 2 °C, and 3 °C. Table 1 summarizes the range of design variables for NMV control strategy.

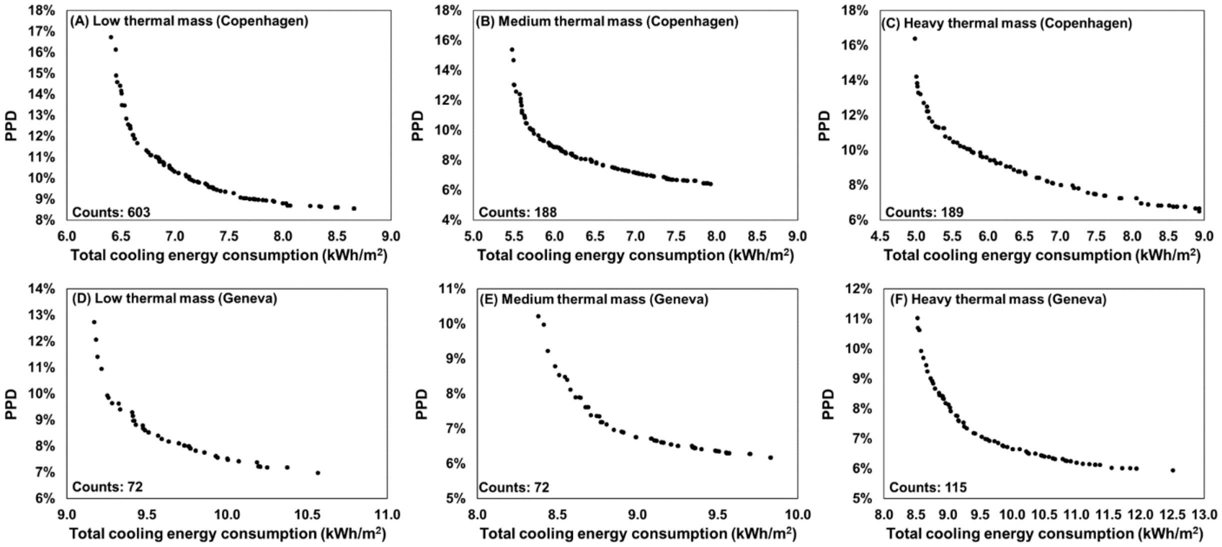
Table 1. Design variables for NMV control strategy

Design variables		Unit	Range
V1	Night ventilation ACH	h^{-1}	0, 1, 2, 3, 4, 5, 6, 7, 8, 9,10
V2	Minimum indoor temperature setpoint	°C	18, 19, 20
V3	Duration	h	(17:00-18:00), (17:00-19:00),…, (07:00-08:00). 120 combinations in total
V4	Threshold temperature	°C	1, 2, 3

3. Results and discussions

3.1. Multi-objective approach

Figure 2 shows the achieved optimal NMV control strategies after 200 generations from the multi-objective optimization in the Pareto fronts under different scenarios, of which the counts means the number of optimal NMV control strategies in the corresponding scenario. All the optimal points on the Pareto front are non-dominated points which both objectives have their optimum values synchronously. It is seen that the two objectives are inversely proportional, representing the contradiction between the pair of objectives. The Pareto curves clearly demonstrate that the impact of climate conditions on the two objectives is much more than that of thermal mass level. Besides, the counts of optimal NMV control strategies indicate that the hotter the climate is, the harder to optimize the two objectives concurrently.



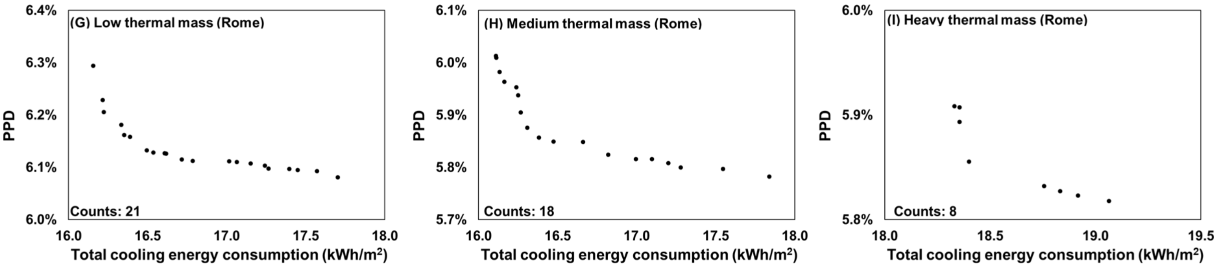


Figure 2. Optimal NMV control strategies on the Pareto-front in different scenarios.

3.2. Final optimal NMV control strategies

A large number of optimal NMV control strategies from the multi-objective approach shows how different objectives influence the optimal NMV control strategy and the interactions of objectives. A satisfactory final optimal solution that comprises both the objectives can be obtained by multiple attribute decision-making methods including the TOPSIS, VIKOR, and ELECTRE methods [16], and dependent on many factors including the importance of each objective, requirements of building design codes, and engineering experience. In this study, a simple method that one criteria for PPD from the recommended category II for the mechanical cooled buildings should less than 10% was selected [8]. Then, the final optimal NMV control strategy for each scenario is the one with the lowest total cooling energy under the premise of fulfilling the acceptable PPD criteria (i.e., less than 10%).

Table 2 and figure 3 depict the design variables and values of two objectives of the base NMV control strategy and final optimal NMV control strategies for different thermal mass levels in diverse climate regions. The symbol (+1) in the third row of table 2 means the next day. As seen from table 2 that the optimum minimum indoor air temperature setpoint (V2) of NMV for the building with low thermal mass in all climates and all buildings in cold climate region is 20 °C. One reason is that the excess heat stored in the buildings with the low thermal mass and the buildings in a cold climate region during daytime can be easily removed by night cooling. Another reason is that the minimum indoor air temperature setpoint can easily be reached after the excess heat was removed that cause the overcooling penalty by increasing the PPD at the beginning of the next working hours. Furthermore, the optimum threshold temperature (V4) for buildings in medium and hot climate region is 3 °C, higher than that in the cold climate region. This indicates more effective heat convection which can be achieved by the high-temperature difference between the ambient air and building elements is needed in the hot climate. The optimum night ventilation ACH (V1) and duration (V3) for all buildings in all climates are smaller than that in base NMV control strategy, except the building with heavy thermal mass level in Rome.

As seen from figure 3, for the base NMV control strategy in different scenarios, the total cooling energy consumption and PPD during occupied hours ranges 5.7 kWh/m^2-18.2 kWh/m^2 and 5.9%-24.5%, respectively. In this respect, the building with heavy thermal mass in cold climate region has the highest PPD, as the heavy thermal mass stores much cooling energy at night and leads to lower indoor temperature. However, the building with heavy thermal mass level in a hot climate region has the highest total cooling energy consumption. One reason is that the hot climate resulting in high AC energy use. Another reason is that the vast excess heat stored in the high thermal mass during daytime needs high NMV energy consumption and may not be fully removed by night cooling with relatively high-temperature ambient air, which leads to more cooling energy use in the following day. Furthermore, for the final optimal NMV control strategies in different scenarios, the total cooling energy consumption varies from 5.6 kWh/m^2 to 18.2 kWh/m^2 and the PPD maintains in the recommended category II for mechanical cooled buildings in EN 15251 [8]. Compared with the base NMV control strategy, the total cooling energy consumption of optimal NMV control strategies reduces 0%-8.6%, while the PPD of optimal NMV control strategies decreases significantly about 0%-59.4%, especially in cold and medium climate region, about 23.6%-59.4%. In hot climate region, the objectives values of optimal NMV control strategies are slightly superior to that of the base NMV control strategy, indicating the optimization benefit of NMV control strategy is not obvious in the hot climate region. Especially for the building with heavy thermal mass level in the hot climate region, whose values of two objectives of the optimal NMV control strategy is the same with the base NMV control strategy. The reason may be that the vast excess heat stored in building elements during daytime and relatively high temperature ambient air at night in hot climate region reduces the possibility of overcooling penalty.

Table 2. Design variables of final optimal NMV control strategies and base NMV control strategy

Design variables	Unit	Base case	Final optimal solution								
			Copenhagen			Geneva			Rome		
			Low	Medium	Heavy	Low	Medium	Heavy	Low	Medium	Heavy
V1	h^{-1}	10	8	4	6	5	5	7	4	6	10
V2	°C	18	20	20	20	20	18	18	20	18	18
V3	h	17-08 (+1)	02-06	19-07 (+1)	20-08 (+1)	22-08 (+1)	21-08 (+1)	20-08 (+1)	18-08 (+1)	17-08 (+1)	17-08 (+1)
V4	°C	3	1	2	2	3	3	3	3	3	3

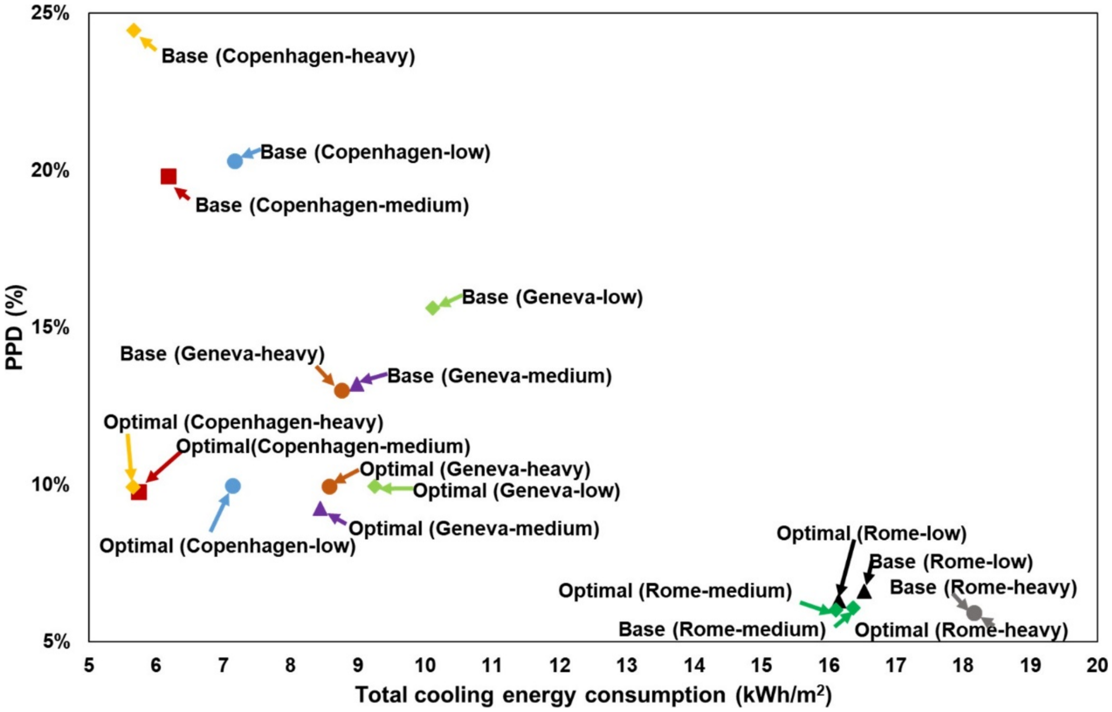


Figure 3. The values of two objectives of the base NMV control strategy and final optimal NMV control strategy in different scenarios.

4. Conclusion

This study proposes a multi-objective optimization based on NSGA II algorithm for NMV control strategy to improve the building energy performance and indoor thermal comfort concurrently for different thermal mass levels in different climate regions. A simple decision-making method based on the acceptable PPD range in EN 15251 is employed to obtain the final optimal NMV control strategy for each scenario. The results show that the total cooling energy consumption of the final optimal NMV control strategies reduces 0%-8.6%, while the PPD decreases 0%-59.4%, compared to the base NMV control strategy. In hot climate region, the values of two objectives of optimal NMV control strategies are only slightly superior to that of the corresponding base NMV control strategy. Even the values of two objectives of the optimal NMV control strategy for the building with heavy thermal mass level is same with the base NMV control strategy. The benefit of NMV control strategy optimization is more obvious in cold and medium climate region. Furthermore, based on the results of Pareto fronts as well as the final optimal NMV control strategies, the climate and thermal mass both have great impacts on the total cooling energy consumption and PPD during occupied hours. It indicates that a well-designed NMV control strategy according to the building configuration and local climate will make a great difference in improving the building energy performance and indoor thermal comfort.

Acknowledgment

This work gratefully acknowledges the financial support from the Chinese Scholarship Council (CSC No. 201706050001).

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