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Research on Flexible Cooling Load Strategy of Air Conditioning in University Classroom Based on Wall Heat Storage and Load Shaving

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ABSTRACT: University teaching buildings constitute a major class of public buildings with high cooling demand and intermittent occupancy patterns. However, the cooling load regulation potential of building envelope thermal mass under inter-zone thermal coupling remains insufficiently quantified in summer cooling contexts. This study aims to quantify the cooling load shaving potential of envelope thermal mass and its underlying mechanisms under inter-classroom thermal coupling, with a focus on intermittent air-conditioning operation in university teaching buildings. A detailed thermophysical model of a representative middle classroom was developed and simulated using EnergyPlus to compare cooling load profiles across five HVAC operation schemes. Wall-surface heat flux integration was employed to elucidate the heat storage and release dynamics governing cooling load regulation. Simulation results indicate that poorly scheduled staggered occupancy triggers a *thermal storage backlash* effect, increasing afternoon cooling loads by 11.5%–11.6%. In contrast, the pre-cooling strategy achieves substantial cooling load reductions of over 20% for afternoon and evening load spikes, at the cost of a 6.2%–7.1% increase in total daily cooling energy. Night-time natural ventilation yields negligible daytime cooling load-shaving benefits (<1%). The hybrid scheme combining pre-cooling and night ventilation marginally outperforms pre-cooling alone, though the additional gain is minimal. Quantitative heat flux diagnostics confirm that pre-cooling redistributes the thermal energy stored within the envelope to align with high-demand cooling load hours, constituting the core mechanism of its load-shaving performance. This study elucidates the time-dependent heat storage and release cycles of partition walls under inter-zonal thermal interactions, providing theoretical support for energy-flexible HVAC scheduling in university classrooms.

KEYWORDS: Envelope heat storage and release; cooling load shaving; EnergyPlus; university classroom; building energy flexibility; HVAC operational strategy

1 Introduction

1.1 Research Background

The increasing share of space cooling in building energy demand has rendered load reduction and efficiency enhancement critical priorities in building energy research. As a core category of public educational infrastructure, campus buildings constitute major contributors to urban energy footprints [1]. In China, higher education institutions account for about 8% of national total energy consumption [2]. The utilization of classrooms in university teaching buildings features intermittent and concentrated cooling demand patterns: HVAC systems operate at full capacity during teaching periods, leading to pronounced temporal

clustering of cooling loads. In this context, optimizing building operation schedules for cooling load shifting and valley filling can mitigate HVAC equipment oversizing while yielding tangible improvements in overall building energy performance.

1.2 Related Work

Classroom partitions in university buildings are typically constructed from high-thermal-mass materials, such as concrete and masonry blocks, which possess substantial thermal storage capacity. Divergent schedules arising from curriculum timetables cause neighboring classrooms to frequently operate under intermittent cooling cycles [3], resulting in cross-wall temperature gradients and inter-zone heat exchange. Such inter-room heat transfer affects indoor thermal comfort and significantly influences overall cooling energy demand.

In recent years, increasing research attention has been given to inter-zone heat exchange within campus teaching facilities. Azar et al. [4] critically reviewed occupant behavior modeling approaches in building performance simulation, emphasizing that occupant-related factors—including cooling setpoints, window operation, and occupancy schedules—significantly affect building thermal loads and should be explicitly considered in energy performance evaluations.

Concerning the underlying mechanisms of inter-zone heat exchange, Xue et al. [5] quantitatively evaluated how inter-room temperature gradients and the number of conditioned zones modulate partition wall heat flux, and identified these two variables as dominant governing factors. Li et al. [6] investigated the coupled dynamic thermal responses of indoor air and building envelopes under intermittent heating, verifying that the conditioning status of adjacent zones substantially alters partition thermal performance. Wang et al. [7] performed parametric numerical analyses on time-variant thermal behaviors of interior partitions under variable heating durations and proposed optimized partition assembly configurations. To evaluate envelope thermal performance under intermittent cooling cycles, Meng et al. [8] confirmed that neighboring HVAC operation markedly modulates partition thermal response speeds and surface heat flux magnitudes, with foam concrete partitions capable of reducing daytime cooling loads by 26.1%.

However, existing literature has predominantly focused on winter heating scenarios, while the coupled interplay between inter-zone heat transfer and partition thermal mass under summer cooling conditions remains insufficiently quantified. To date, few quantitative studies have characterized how inter-classroom thermal coupling reshapes the time-dependent heat storage-release cycles of partition walls during summer cooling operations. Moreover, cross-room heat exchange can either facilitate cooling load regulation (with partitions acting as thermal reservoirs that absorb or release heat between zones) or trigger adverse load amplification if operational scheduling is poorly designed.

To address these research gaps, the present work systematically investigates how controlled HVAC scheduling schemes—including staggered occupancy and pre-cooling—differentially modulate cooling loads by manipulating partition wall thermal mass dynamics. Unlike prior studies that mainly report aggregate energy savings or thermal comfort impacts, our contribution provides: (1) a quantitative characterization of the time-dependent charging-discharging cycles of partition walls under summer inter-zone thermal coupling; (2) identification and mechanistic explanation of the ‘*thermal storage backlash*’ phenomenon in this context; (3) wall-surface integrated heat flux diagnostics that establish causal linkages between specific scheduling decisions and observed cooling load-load outcomes. This mechanistic focus distinguishes our work from prior parametric studies and offers actionable insights for campus HVAC schedule design.

2 Methods and Models

2.1 Basis for Selecting Architectural Models and Intermediate Classrooms

This work adopts a simplified numerical model of a three-story, north-south-oriented university teaching building. Each floor contains nine linearly arranged classrooms along one facade, with an unconditioned corridor running adjacent to the classroom row. While most real-world campus teaching buildings adopt a double-corridor central layout, the single-sided corridor simplification used herein prioritizes the analysis of partition wall thermal mass dynamics without altering the qualitative trends governing inter-partition heat transfer. The single-sided corridor configuration results in corridor air temperatures closer to outdoor ambient conditions, which may slightly overestimate the cooling potential of overnight natural ventilation, while the relative ranking of all tested operational schemes remains unchanged. To quantify the effects of facade orientation on envelope thermal mass behavior, two independent simulation configurations were established by rotating the entire three-story building model by 180° about its vertical axis. This rotation reverses the glazing azimuth for all classrooms simultaneously—yielding south-facing and north-facing configurations—while preserving all geometric dimensions, material properties, internal load profiles, and HVAC operational schedules. Notably, this whole-building rotation ensures that the target classroom (Room 5) and all four adjacent conditioned zones (Rooms 2, 4, 6, and 8) undergo consistent orientation changes, thereby maintaining the original inter-zone spatial relationships and enabling a fair comparison of solar radiation impacts on the target zone's cooling load without introducing confounding asymmetries.

Room 5, a mid-unit classroom on the second floor, was designated as the primary target space, with four adjacent conditioned zones (Rooms 2, 8, 4, and 6) located above, below, to the left, and to the right. This choice is justified by the fact that the thermal performance of interior zones in educational buildings is governed primarily by inter-zonal heat transfer through partition walls and internal thermal mass, whereas perimeter zones are dominated by external envelope heat exchange and solar gains—a distinction that has been demonstrated to significantly affect cooling load profiles in intermittently conditioned spaces [9].

It should be noted that our model does not introduce new numerical algorithms. The novelty lies instead in the application domain: we identify and quantitatively explain the '*thermal storage backlash*' phenomenon under inter-classroom cooling mismatch, and we use heat flux diagnostics to reveal why certain operational strategies are effective while others backfire—a mechanistic question that has not been previously addressed for summer cooling in university buildings.

Glazing units are modeled with dimensions of 2 m (width) $\times$ 3 m (height), corresponding to a window-to-wall ratio of 34%. Each classroom is modeled with internal dimensions of 10.0 m (length) $\times$ 6.0 m (width) $\times$ 3.5 m (floor-to-floor height). For infiltration modeling, window frames are assigned an effective leakage area of 80 cm^2 , with both stack and wind coefficients set to 0.15 for natural ventilation calculations. The interior door infiltration rate is specified as $0.00008 \text{ m}^3/(\text{s}\cdot\text{m}^2)$, calculated according to the methods prescribed in GB 50736-2012 [10]. Internal heat gains from occupants are set to 120 W per person, with sensible and latent portions automatically partitioned by the EnergyPlus thermal comfort model; radiant fractions are 0.3 for occupants, 0.7 for lighting, and 0.3 for equipment. The cooling setpoint, HVAC operation schedules, and outdoor air ventilation rate are described in Sections 2.3 and 2.5. A three-dimensional geometric model was constructed using EnergyPlus Version 23.2. All classroom zones were defined as conditioned spaces, while corridors were left unconditioned but fully coupled to thermal exchange calculations. Fig. 1 presents a schematic diagram of the simulated teaching building model.

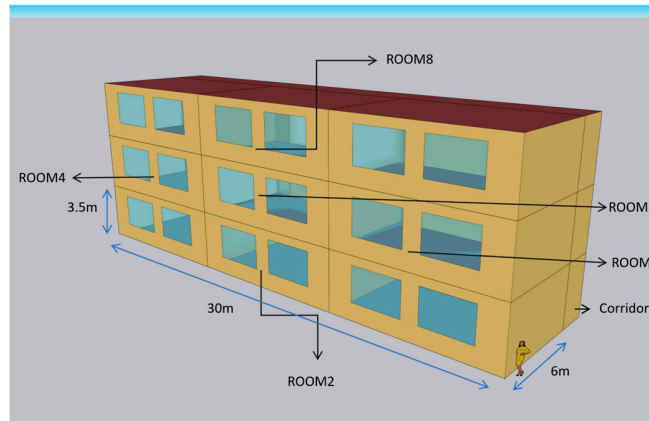


Figure 1: Schematic diagram of the simulated teaching building model.

2.2 Thermal Parameters of Envelope

All assembly configurations and material thermal properties for building envelopes were specified in compliance with GB 50176-2016, Thermal Design Code for Civil Buildings [11]. Full geometric and thermal property data are summarized in Table 1.

Table 1: Assembly configurations and thermophysical parameters of building envelope components.

Envelope Component	Layer Sequence (Exterior to Interior)	Thickness (mm)	Thermal Conductivity ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$)	Density ($\text{kg}\cdot\text{m}^{-3}$)	Specific Heat Capacity ($\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$)
External wall	Ceramic tile + polymer anti-crack mortar + cement mortar + aerated concrete block + composite mortar	255	0.21	900	1000
Partition wall	Composite mortar + concrete hollow block + composite mortar	240	0.81	1267	1011
Glazing	Single clear white glass	6	0.9	2500	840
Inter-floor slab	Floor tile + cement leveling mortar + reinforced concrete + composite mortar	185	1.08	2150	970
Roof assembly	Fine aggregate concrete + SBS modified asphalt waterproof membrane + cement mortar + extruded polystyrene + cement expanded perlite + reinforced concrete roof slab + composite mortar	310	0.19	1340	1000
Ground slab	Concrete bedding + waterproof membrane + fine aggregate concrete + cement mortar + floor tile	225	1.2	2100	970

Table 1: *Cont.*

Envelope Component	Layer Sequence (Exterior to Interior)	Thickness (mm)	Thermal Conductivity ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$)	Density ($\text{kg}\cdot\text{m}^{-3}$)	Specific Heat Capacity ($\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$)
Interior door	Plywood wooden door	45	0.16	650	1800

Note: The thermal conductivity, density, and specific heat values presented in Table 1 are equivalent properties for each complete assembly, derived from the layer-by-layer material properties specified in GB 50176-2016. In the actual EnergyPlus model, each layer was individually defined with its own thickness and thermophysical properties rather than using a single equivalent layer; the tabulated equivalent values are provided for concise reporting of overall assembly characteristics.

2.3 Internal Loads and HVAC Settings

Occupancy density was specified as follows. Each classroom was designed for a maximum occupancy of 30 occupants, with time-varying occupancy levels defined according to standard university timetables. Based on actual campus teaching routines, occupancy was set to 90% capacity (27 occupants) during instructional periods and 50% capacity (15 occupants) during inter-class breaks to replicate student ingress and egress dynamics. Detailed daily teaching timetables are listed in Table 2.

Table 2: Timetable of instructional and inter-class periods.

Session 1	08:10–08:55	Session 7	15:15–16:00
Session 2	09:00–09:45	Session 8	16:05–16:50
Session 3	10:00–10:45	Session 9	18:30–19:15
Session 4	10:50–11:35	Session 10	19:20–20:05
Session 5	13:30–14:15	Session 11	20:10–20:55
Session 6	14:20–15:05		

For the supplementary weekly simulation (July 18–24), the same operational schedules (occupancy, HVAC, lighting, and equipment) as the weekday timetables (Table 2) were applied consistently across Saturday and Sunday.

A supplementary timetable survey was conducted across major Hangzhou higher education institutions (Zhejiang University, Zhejiang University of Technology, and Hangzhou Dianzi University) to validate the representativeness of the scheduling framework in Table 2. Survey results indicate that morning instruction begins between 08:00 and 08:20, afternoon sessions commence from 13:10 to 13:30, and evening courses or self-study generally start at approximately 18:30, with uniform 45-min instructional periods consistent with standard campus scheduling norms. The adopted timetable (08:10–11:35, 13:30–16:50, 18:30–20:55) closely matches routine arrangements at the surveyed universities and offers high practical representativeness for cooling demand modeling in Hangzhou regional campus buildings.

Door operational schedules: Classroom doors remained fully closed during teaching hours and open during inter-class intervals to capture the effects of natural ventilation and occupant flow on indoor thermal conditions. Corridors were treated as unconditioned zones; door open/closed states were scheduled using EnergyPlus's ventilation availability schedule module.

Internal heat gains from equipment and lighting: Each classroom contained 800 W of electrical equipment loads (projectors, desktop computers, and auxiliary devices) and 300 W of LED grille luminaire lighting loads.

HVAC configuration: The EnergyPlus Ideal Loads Air System was implemented to isolate partition thermal mass mechanisms by removing dynamic response noise from physical HVAC hardware; real-world pre-cooling performance may be somewhat lower than simulated values. The cooling setpoint temperature

was fixed at 26°C [12]. HVAC systems operated continuously throughout all instructional and inter-class periods and were fully deactivated during midday and overnight off-hours. The Ideal Loads Air System was selected to isolate thermal mass effects from hardware-related transients, such as compressor cycling, fan speed modulation, and supply air temperature fluctuations. This approach ensures that the observed differences in cooling load magnitudes across the five operational schemes are attributed exclusively to envelope thermal storage dynamics rather than equipment performance characteristics. While this simplification may overestimate the theoretical cooling load-shaving potential relative to actual operating conditions, it preserves the relative ranking of all tested strategies and provides a conservative upper-bound benchmark for real-world applications. The practical feasibility of each scheme is further discussed in Section 4.4.

2.4 Operation Strategy Design

Five distinct HVAC operational schemes (Cases 1–5) were defined to compare and quantify cooling load-load reduction performance across diverse scheduling logics, as detailed in Table 3.

Table 3: Definition of HVAC operational test schemes.

Scheme ID	Operational Description
Case 1 (Baseline)	Synchronized HVAC operation across all zones: 08:10–11:35, 13:30–16:50, 18:30–20:55
Case 2 (Staggered HVAC operation)	Desynchronized scheduling for Room 5 relative to adjacent zones (Room 2, 4, 6, 8). Neighboring zones conditioned during 08:10–11:35 and 18:30–20:55; Room 5 conditioned only during 13:30–16:50 and 18:30–20:55
Case 3 (Standalone pre-cooling)	HVAC activated 30 min prior to Room 5 occupancy (07:40–08:10 and 13:00–13:30) to pre-condition indoor air to the 26°C setpoint, maintaining the target temperature during scheduled occupancy
Case 4 (Overnight natural ventilation only)	Overnight natural ventilation from 20:55 to 08:10 the following day at an air change rate of 3 h ⁻¹ [10], assuming windows are manually opened by occupants after class and remain open overnight.
Case 5 (Hybrid pre-cooling + overnight ventilation)	Overnight natural ventilation activated 20:55–07:40 daily, paired with identical pre-cooling timings specified for Case 3

All five schemes were simulated twice (south-facing and north-facing glazing) to isolate facade orientation impacts on thermal mass and cooling load profiles.

2.5 Simulation Settings and Output Variables

Meteorological boundary conditions: Standard EnergyPlus.epw typical meteorological year datasets for Hangzhou were adopted [13].

Simulation timeline: Two critical design days were simulated: January 21 (winter design day) and July 21 (summer design day). To account for antecedent thermal conditions, a supplementary weekly simulation (July 18–24) was also performed. The present analysis prioritizes summer cooling performance.

Output monitoring variables: Time-series outputs were recorded at 5-min intervals for the following metrics: instantaneous cooling load of each Room [W], indoor air temperature of each Room [°C], surface temperatures of all partition walls bounding each Room [°C], and instantaneous inter-partition surface

heat flux [W] (with the sign convention defined below in Section 3.2). All instantaneous heat flux values were numerically integrated over specified time intervals to obtain cumulative heat transfer [kWh] for the analyses presented in Tables 4 and 5.

Table 4: Cooling loads and total daily cooling energy demand across all test schemes.

Test Scheme	Morning Cooling Load/W	Afternoon Cooling Load/W	Night Cooling Load/W	Total Cooling Energy/kWh
Case 1 South	4200	7851	6336	35.927
Case 1 North	4060	7510	6261	35.226
Case 2 South	0	8755	7207	27.381
Case 2 North	0	8381	7069	26.745
Case 3 South	4181	6235	4783	38.306
Case 3 North	4041	5873	4753	37.539
Case 4 South	4154	7776	6271	35.526
Case 4 North	4013	7436	6195	34.817
Case 5 South	4138	6158	4728	37.721
Case 5 North	3997	5797	4696	36.928

Cooling load discrepancies between south and north orientations ranged from 5% to 8%, driven primarily by differential solar irradiance gains; nevertheless, the relative performance hierarchy of all five schemes remained consistent regardless of facade azimuth.

Table 5: Daily cooling loads from the supplementary weekly simulation (July 18–24).

Test Scheme	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Weekly Total (kWh)
Case 1 South	6980	7851	7960	7710	8020	7680	7130	247.8
Case 1 North	6670	7510	7620	7370	7680	7340	6810	237.0
Case 2 South	7710	8755	8880	8600	8940	8560	7880	189.6
Case 2 North	7380	8381	8500	8230	8560	8190	7540	181.4
Case 3 South	5530	6235	6320	6120	6370	6090	5650	264.1
Case 3 North	5210	5873	5960	5760	6010	5730	5320	258.8
Case 4 South	6910	7776	7880	7630	7940	7600	7060	245.0
Case 4 North	6600	7436	7540	7290	7600	7260	6740	240.0
Case 5 South	5470	6158	6240	6040	6290	6010	5590	260.1
Case 5 North	5150	5797	5890	5690	5940	5660	5260	254.7

The weekly data confirm that the relative performance hierarchy of the five schemes—with Cases 3 and 5 consistently achieving the lowest cooling loads (Case 5 marginally outperforming Case 3) and Case 2 the highest—remains consistent throughout the week, aligning with the design-day observations.

2.6 Model Credibility

The credibility of the simulation framework rests on the following foundations. EnergyPlus is an extensively validated building energy simulation engine that has been empirically benchmarked against experimental data under the ANSI/ASHRAE Standard 140 framework [14], and its airflow network model has been validated against field measurements [15]. Furthermore, its internal thermal mass simulation

has demonstrated a mean absolute error of 0.8°C in interior temperature predictions [16]. All envelope thermophysical properties were specified in accordance with GB 50176-2016 [11], whose material parameters were empirically determined through systematic laboratory testing. Since this study focuses on relative comparisons among five operational schemes under identical boundary conditions, systematic errors tend to cancel out, making the conclusions robust to minor absolute inaccuracies. To further substantiate the credibility of the present model for the specific classroom typology and inter-zonal thermal coupling conditions investigated, we note that the model input configurations adopted in this study are consistent with those of published studies that have been validated against field measurements in comparable contexts. Specifically, Li et al. [17] conducted field measurements in a university classroom in Chengdu (hot-summer and cold-winter climate zone) and employed EnergyPlus to investigate dynamic heat transfer through interior partition walls under intermittent conditioning, confirming that the simulation framework reliably captures the thermal dynamics of partition walls in university classrooms. Ge et al. [18] performed extensive field measurements in a university research building in Hangzhou—the same city and climate zone as the present study—and subsequently developed an EnergyPlus model validated against the measured data. These references demonstrate that the model settings used in this work are consistent with validated models for similar university classroom buildings in hot-summer and cold-winter climates. Additionally, since this study focuses on relative comparisons among five operational schemes under identical boundary conditions, systematic modeling uncertainties apply equally to all schemes and do not affect the relative performance hierarchy or the mechanistic conclusions.

3 Results

3.1 Comparison of Design Daily Load Curves

Hourly cooling load profiles for Room 5 across all five schemes were plotted for the summer design day (21 July), as shown in Fig. 2. Cooling loads and cumulative daily cooling energy for each orientation and operational scheme are summarized in Table 4. Daily cooling loads and weekly cumulative cooling energy from the supplementary weekly simulation are presented in Table 5 for reference.

Fig. 2 and Table 4 show that the baseline Case 1 exhibits pronounced bimodal cooling load signatures for both orientations: a morning cooling load emerges at 11:35 (end of morning instruction), while a prominent afternoon cooling load occurs at 13:35 (start of afternoon teaching sessions). South-facing zones consistently exhibit higher cooling loads owing to increased solar radiative heat gains [19]. Under the staggered occupancy scheme (Case 2), afternoon cooling load magnitudes increased rather than decreased. This adverse response is formally defined herein as *thermal storage backlash*, which describes load amplification triggered by temporal mismatch between partition thermal mass charging cycles and classroom occupancy demand. The standalone pre-cooling scheme (Case 3) achieves substantial attenuation of afternoon and evening load spikes, although it incurs additional cooling demand during pre-conditioning periods. Morning cooling load magnitudes remain nearly unchanged, attributed to naturally low indoor air temperatures overnight. Despite a moderate rise in cumulative daily cooling energy relative to the baseline, the scheme achieves marked cooling load suppression. The overnight ventilation-only scheme (Case 4) has negligible mitigating effects on daytime cooling loads, reducing total daily energy demand by only 1%. The hybrid scheme (Case 5), integrating pre-cooling and overnight natural ventilation, further reduces afternoon cooling loads to 6158 W (21.6% reduction) for south-facing zones and 5797 W (22.8% reduction) for north-facing zones. Although the hybrid scheme marginally outperforms pre-cooling alone, the incremental performance improvement is minimal (<1%).

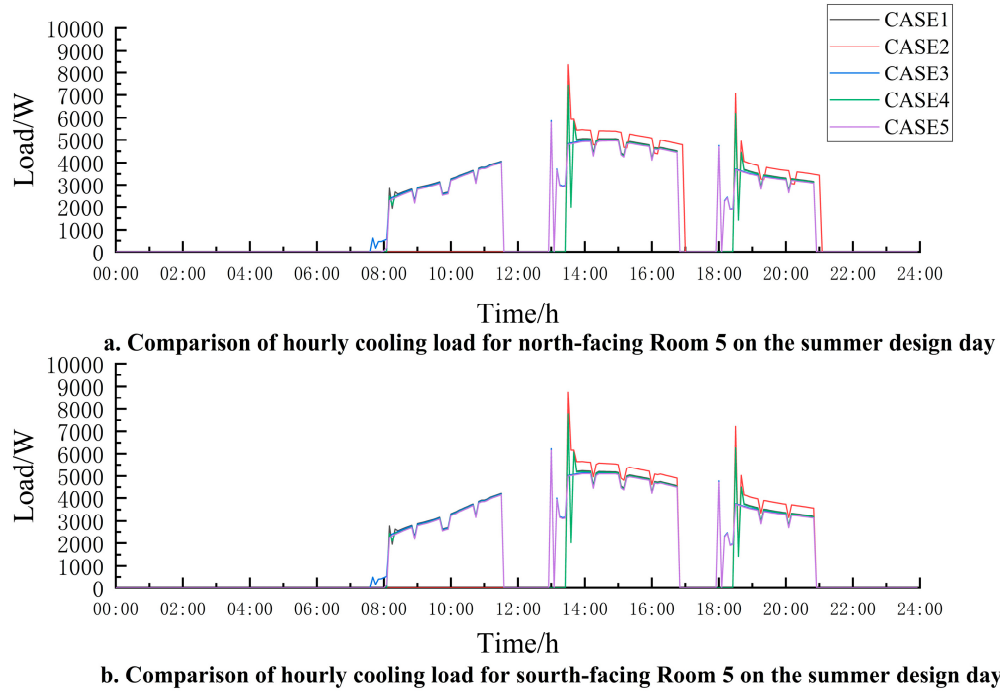


Figure 2: Hourly cooling load profiles of Room 5 on the summer design day: (a) north-facing; (b) south-facing.

3.2 Heat Flux and Temperature Response of Wall Surface under Operation Strategy

To elucidate the thermal mechanisms underlying cooling load modulation under distinct HVAC schedules, this section analyzes surface heat flux and temperature variations of all bounding surfaces of Room 5—including the west/east partition walls (shared with Rooms 4 and 6), the ceiling/floor slabs (shared with Rooms 2 and 8), the north external wall, and the south corridor wall. Since all six surfaces exhibit qualitatively similar temporal trends under each operational scheme, the west partition wall is used here as a representative example, while Table 6 reports the quantitative integrated heat fluxes of the four room-adjacent surfaces during three critical periods for Case 2. A consistent sign convention is used throughout: negative values represent heat transfer from indoor air into the partition (thermal mass charging), while positive values correspond to heat released from the partition to indoor air (thermal mass discharging).

Table 6: Integrated heat fluxes of four room-adjacent surfaces of Room 5 during critical periods (kWh).

Surface	Adjacent Room	Morning (08:00–11:00)	Afternoon (14:00–17:00)	Evening (19:00–21:00)
West wall	Room 4	−0.585	0.007	0.176
East wall	Room 6	−0.540	0.006	0.162
Ceiling slab	Room 2 (above)	−2.34	0.028	0.704
Floor slab	Room 8 (below)	−2.20	0.025	0.660
Total	—	−5.665	0.066	1.702

The north external wall and south corridor wall are not included in Table 6, as they are not relevant to the inter-zonal thermal coupling mechanism that is the focus of this study; their heat fluxes are governed by outdoor climate and corridor conditions rather than adjacent classroom HVAC schedules.

3.2.1 Temporal Comparison of Wall Heat Flux under Synchronous and Staggered Conditions

Fig. 3 illustrates minute-by-minute heat flux trends across the shared partition between Room 5 (west surface) and Room 4 (east surface) under Cases 1 and 2. Cross-analysis of partition surface temperature profiles for both zones reveals the fundamental inter-partition heat exchange mechanisms that govern cooling load formation.

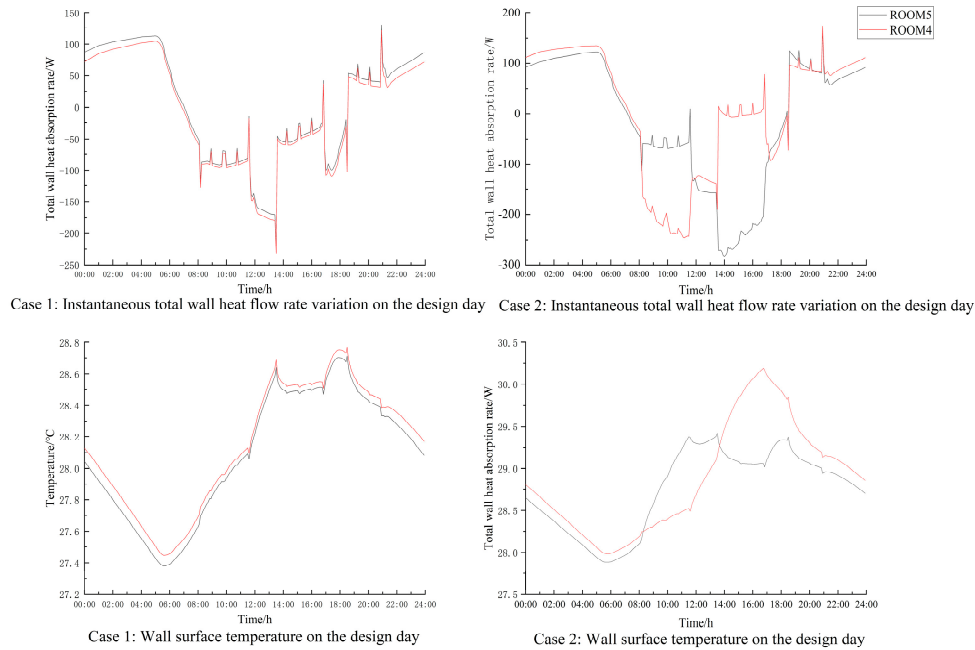


Figure 3: Time-series evolution of partition surface heat flux and surface temperature for Case 1 and Case 2 on the summer design day.

For Case 1 (synchronized occupancy), both zones activate and deactivate cooling simultaneously, resulting in symmetric diurnal thermal mass cycling: positive heat flux values indicate overnight thermal mass discharge, while negative values denote daytime thermal mass charging. Under synchronized scheduling, the full thermal storage capacity of the partition remains underutilized.

In contrast, Case 2 (staggered occupancy) exhibits markedly different thermal dynamics: from 08:00 to 11:35, Room 4 is cooled while Room 5 remains unconditioned; cross-zone temperature gradients drive substantial heat transfer from Room 5 toward cooled Room 4, inducing extreme negative heat flux cooling loads below -7017 W on the Room 5 partition face—2.3 times the cooling load magnitude recorded in Case 1. Once cooling commences in Room 5 between 13:30 and 16:00, the partition releases thermal energy accumulated during the morning hours, generating additional sensible cooling loads within the target classroom.

3.2.2 Comparison of Wall Thermal Charging and Discharging Characteristics

To quantify how different HVAC scheduling modulates partition thermal mass charging and discharging dynamics, Fig. 4 shows continuous time-series profiles of west partition surface heat flux and indoor air temperature for north-facing Room 5 across all five test schemes. Integrated cumulative heat transfer magnitudes over critical daily intervals were calculated to elucidate the causal relationship between partition thermal cycling and cooling load suppression.

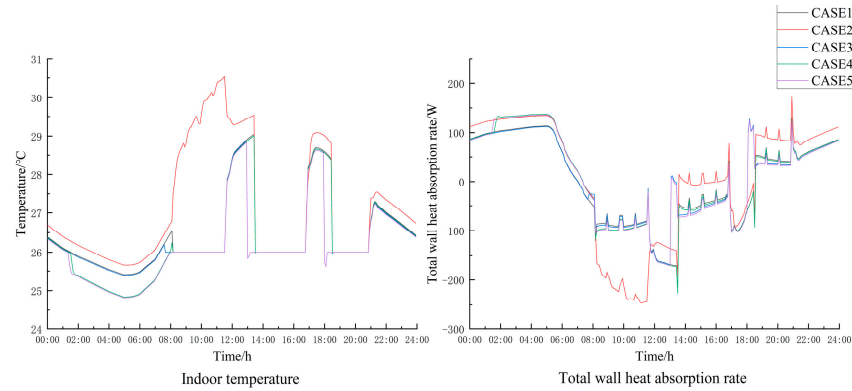


Figure 4: Partition surface heat flux and indoor air temperature time series (west partition of north-facing Room 5) for all five operational schemes.

(1) Overnight thermal mass discharging phase

During overnight periods when HVAC systems are deactivated, partitions release the thermal energy (heat) accumulated during daytime, manifesting as positive surface heat flux values. Cumulative overnight thermal discharge (integrated heat flux summed over an 8-h window from 23:00 to 07:00) for each scheme is presented in Table 7.

Table 7: Cumulative overnight thermal discharge energy (kWh).

Test Scheme	Case 1	Case 2	Case 3	Case 4	Case 5
Cumulative overnight discharge	0.712	0.897	0.700	0.840	0.831

Table 5 shows that Case 2 produces the largest overnight thermal discharge volume, corresponding to a 26.0% increase over the baseline Case 1. Case 4 and Case 5 also show elevated overnight discharge relative to the baseline. This indicates that overnight natural ventilation lowers both partition surface and indoor air temperatures, which widens the partition-to-indoor temperature gradient and accelerates nocturnal thermal mass discharge.

(2) Diurnal partition thermal charging and discharging cycles

Time-varying partition heat flux signatures during occupied hours directly reveal the load-shaving mechanisms inherent to each scheduling scheme. Table 8 summarizes the integrated heat flux over three critical diurnal windows: morning (08:00–11:00), afternoon (14:00–17:00), and evening (19:00–21:00).

Table 8: Cumulative heat transfer across three key diurnal periods (kWh).

Test Scheme	08:00–11:00 Thermal Charging	14:00–17:00 Thermal Charging	19:00–21:00 Thermal Discharging
Case 1	0.255	0.129	0.086
Case 2	0.585	−0.007	0.176
Case 3	0.253	0.151	0.069
Case 4	0.275	0.139	0.082
Case 5	0.276	0.160	0.065

Diurnal partition thermal cycling directly governs the temporal distribution of cooling load cooling loads. Morning thermal charging magnitudes for Case 2 substantially exceed those of all other schemes, reaching more than double the integrated charging load observed in Case 1. Conversely, Case 3 and Case 5 exhibit enhanced thermal storage capacity during afternoon cooling load demand periods, along with reduced evening thermal mass discharge.

3.3 Analysis of the Influence of Dynamic Occupancy Variation and Door Opening and Closing Behavior

Three auxiliary sensitivity test schemes were defined based on the baseline Case 1 to isolate and quantify the independent cooling load perturbations arising from dynamic occupancy variation and inter-class door operation schedules, as detailed in Table 9.

Table 9: Definition of sensitivity analysis test schemes.

Sensitivity Scheme	Boundary Condition Modification Relative to Case 1 Baseline
Case 1a	All baseline internal heat gains retained; classroom doors permanently closed (no inter-class natural ventilation)
Case 1b	Baseline door operation and equipment/lighting loads retained; fixed occupancy held at 90% capacity throughout all timetables (no inter-class occupancy reduction)
Case 1c	Combined modification: permanent door closure + fixed 90% full occupancy across all hours

Individual thermal impacts from door ventilation and occupancy variability were decoupled via pairwise comparison between the baseline and three sensitivity schemes. Cumulative daily cooling energy for all four sensitivity test cases on the summer design day are plotted in Fig. 5.

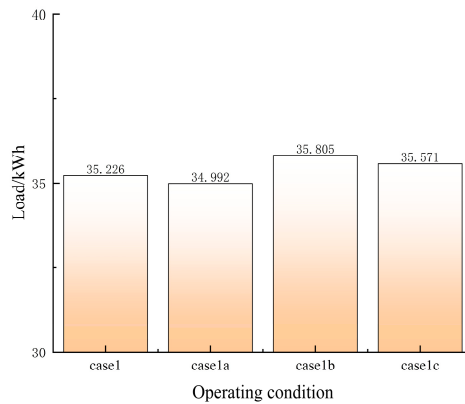


Figure 5: Impacts of dynamic occupancy and inter-class door operation on total daily cooling energy.

Simulation results show that intermittent door opening between classes results in total cooling load deviations of less than 1%, attributable to the short opening duration and limited heat exchange with the unconditioned corridor, whereas changes in student occupancy alter overall cooling demand by less than 2%. Within the boundary conditions of this numerical model, temporary occupancy changes and periodic door ventilation are only minor secondary factors affecting partition thermal cycling and cooling load magnitudes, while HVAC operational scheduling remains the dominant factor governing overall building cooling load characteristics.

4 Discussion

4.1 Temporal Mismatch of Partition Thermal Mass Cycling and the Thermal Storage Backlash Phenomenon

Simulation results show that desynchronized occupancy scheduling between the target zone and adjacent conditioned rooms (Case 2) increases afternoon cooling load magnitudes by 11.5%–11.6% compared with the synchronized baseline Case 1. This adverse load response is formally defined as *thermal storage backlash*.

This *thermal storage backlash* is conceptually distinct from the ‘load rebound’ effect commonly discussed in demand response literature. Rebound typically denotes transient power surges following control recovery, whereas the backlash identified here arises from spatial mismatches in adjacent classroom schedules—the partition absorbs heat from the warmer target room during the morning (while adjacent cooled zones maintain lower partition surface temperatures), storing thermal energy within the wall mass; when cooling is activated in the target classroom in the afternoon, the partition releases this stored heat back into the indoor air, thereby amplifying cooling loads. To the best of our knowledge, this spatial mechanism has not been previously quantified for summer classroom cooling, as existing research has predominantly focused on winter heating scenarios.

The underlying physical mechanism driving the backlash effect is as follows: neighboring zones are cooled during morning hours, reducing partition surface temperatures, while the unconditioned target classroom maintains higher indoor air temperatures. This cross-zone temperature gradient drives substantial thermal energy storage within the shared partition throughout the morning period. When cooling is activated in the target classroom during the afternoon, the partition releases the stored thermal energy into the indoor air, generating additional, unanticipated cooling demand.

This observation demonstrates that temporal misalignment between thermal mass charging cycles and occupancy schedules—rather than simply the magnitude of inter-zone heat flux—is the primary driver of cooling load amplification. This confirms that partition thermal mass does not always act as a beneficial thermal buffer under intermittent cooling operation; poorly coordinated HVAC scheduling can exacerbate cooling loads. This conclusion provides practical guidance for demand-side management in campus buildings: staggered occupancy schemes should be validated via dynamic thermal simulation before deployment, as unoptimized desynchronization can produce counterproductive cooling load amplification.

4.2 Core Cooling Load Shaving Mechanism of Pre-Conditioning Scheduling

The fundamental load-reduction mechanism of pre-cooling lies in reshaping the diurnal charging-discharging cycle of partition thermal mass. Pre-conditioning cools building partitions in advance, lowering their surface temperatures and thereby storing cooling capacity during off-cooling load periods, while also enabling the envelope to absorb excess sensible heat during afternoon demand spikes. This creates a beneficial temporal redistribution of thermal energy: thermal storage is accumulated ahead of high-demand hours and instantaneously deployed to offset cooling loads once occupancy begins. This process transforms static partition assemblies from passive thermal buffers into controllable flexible demand-response assets. This mechanistic interpretation aligns with prior parametric and control studies by Lu et al. [20] and Kyojuka et al. [21], who confirmed that pre-cooling high-thermal-mass envelopes offers substantial cooling load demand shifting potential. Despite its effective cooling load suppression performance, pre-cooling incurs additional total cooling energy consumption. Practical economic feasibility must therefore be evaluated holistically against pre-conditioning duration and time-of-use electricity pricing frameworks for real-world deployment.

4.3 Marginal Performance Gains and Climate-Dependent Applicability of Hybrid Scheduling Schemes

The hybrid pre-cooling plus overnight ventilation scheme (Case 5) offers only marginal additional cooling load-load reduction compared with standalone pre-cooling. This limited supplementary benefit arises from Hangzhou's summer nighttime thermal conditions: typical meteorological year data show an average July overnight minimum temperature of approximately 26.5°C. Under such conditions, natural cross-flow ventilation cannot cool partition surfaces below the 26°C cooling setpoint, effectively eliminating any meaningful additional thermal storage via overnight passive cooling.

By contrast, in regions where nighttime ambient temperatures are lower, overnight natural ventilation can more fully activate building thermal mass and reduce total cooling energy demand [22]. Furthermore, when combined with model predictive control, overnight ventilation can further reduce operational costs and carbon emissions under time-of-use electricity pricing or on-site photovoltaic generation frameworks [23].

4.4 Research Limitations and Prospects

This numerical investigation has several inherent limitations. First, the single-sided corridor layout adopted for model simplification deviates from the widely used double-central-corridor design in real campus teaching buildings and may alter the thermal exchange pathways between unconditioned corridors and conditioned classrooms. Second, advanced active thermal storage technologies, such as phase change materials (PCMs) [24,25], were excluded from the current parametric analysis, although their integration into partition assemblies could substantially enhance the envelope's peak-shaving and valley-filling capacity. Additionally, the use of the Ideal Loads Air System in this study represents a theoretical upper-bound estimate of peak-shaving performance. In practice, variable refrigerant flow (VRF) or variable air volume (VAV) systems exhibit part-load performance degradation and non-linear coefficient of performance (COP) curves, which may yield smaller demand reductions than those reported here. Future work should incorporate actual HVAC equipment models with empirical performance maps to validate the practical demand flexibility of the proposed scheduling schemes. Third, all tested HVAC scheduling schemes rely on static fixed timetables without incorporating real-time dynamic optimization algorithms, including model predictive control (MPC) [26–28], despite the stochastic occupancy fluctuations observed in real campus teaching scenarios. Fourth, the thermal storage backlash phenomenon identified in this study has been verified under south- and north-facing orientations, but its generalizability across broader geometries, climate zones, and classroom positions warrants further investigation. Fifth, the overnight ventilation strategy currently employs temperature-based control only; humidity-triggered control is not natively supported by the EnergyPlus simple ventilation module and awaits incorporation in future model refinements.

Future work can extend the present findings by: (1) constructing a double-central-corridor numerical model to verify the generalizability of the thermal mass and peak-load conclusions derived in this paper; (2) exploring the synergistic cooling performance and quantifiable peak-shaving potential of PCM-enhanced partition walls paired with pre-conditioning schemes; (3) developing data-driven partition thermal mass prediction frameworks to support self-adaptive real-time HVAC schedule optimization; and (4) conducting cross-climate comparative simulations to benchmark the practical suitability of the proposed load regulation strategies across cold, temperate, and hot-humid climate zones.

5 Conclusions

This work employed EnergyPlus-based dynamic thermal simulations to characterize cooling load profiles and the charging and discharging dynamics of partition thermal mass in a representative university

classroom under five distinct HVAC operational schemes. Cumulative wall-surface heat flux integration was used to quantitatively elucidate the core thermal mechanisms underlying cooling load modulation.

1. Improper staggered occupancy scheduling triggers the *thermal storage backlash* effect, elevating afternoon cooling loads by 11.5%–11.6% due to temporal mismatch between partition thermal cycling and classroom occupancy demand.
2. Standalone pre-conditioning reshapes diurnal partition thermal mass cycles to deliver cooling load reduction exceeding 20%. This scheme boosts afternoon (14:00–17:00) thermal charging magnitude by 16.6% and reduces evening (19:00–21:00) thermal discharge by approximately 20% (see Table 8), at the expense of a moderate 6.2% rise in total daily cooling energy demand.
3. Overnight natural ventilation delivers negligible daytime cooling load suppression (<1%) under Hangzhou's summer nocturnal high-temperature climate; hybrid pre-cooling plus ventilation yields only marginal supplementary cooling load-shaving benefits with limited performance uplift.
4. The wall-surface integrated heat flux methodology validated in this study provides a robust quantitative tool to establish causal linkages between partition thermal mass behavior and temporal cooling load magnitudes.

The inter-zone thermal coupling and load-shaving outcomes derived from this work provide actionable theoretical guidance for designing energy-flexible HVAC scheduling schemes for intermittently occupied university teaching buildings in hot-summer and cold-winter climate zones.

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