



Thermal Inertia and Seasonal Energy Performance of CLT Office Buildings in Japan: A Case Study Based on Monitoring

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Abstract

Improving building energy flexibility and reducing peak demand are critical challenges in energy systems, particularly in regions experiencing supply constraints. Cross-Laminated Timber (CLT) buildings, due to their thermal inertia, offer potential for enhancing energy efficiency and supporting demand response strategies.

This study investigates the dynamic thermal behavior of a CLT office building in Japan using in-situ monitoring under both winter and humid summer conditions. Key thermal inertia indicators, including attenuation coefficient and time delay, were derived from measured temperature data to assess transient thermal response and interaction with HVAC operation. The results show that the CLT building exhibits strong thermal buffering capacity, with clear attenuation and time-delay effects observed under both seasonal conditions. The observed time-delay behavior and gradual temperature decay indicate reduced HVAC cycling and improved operational stability under both heating and cooling conditions. These findings demonstrate that CLT buildings can support energy-efficient HVAC operation and flexible demand response strategies. The study provides empirical evidence for integrating CLT into climate-responsive and low-carbon building design, with implications for grid-interactive energy management.

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Keywords

Cross-Laminated Timber; Dynamic thermal inertia; HVAC interaction; Demand response; Field monitoring

1. Introduction

1.1 Energy Systems and Demand Response Context

Energy conservation is critical for mitigating climate change and addressing power shortages. Following the 2011 Great East Japan Earthquake, Japan experienced severe electricity shortages, leading to significant reductions in air conditioning (AC) use. However, existing studies are often based on aggregated data and lack building-level reproducibility. This study addresses this gap through in-situ monitoring of a CLT office building under controlled conditions. Power demand typically exhibits daily fluctuations with distinct peak periods, especially in summer due to air conditioning loads and in winter due to heating demand.

Office buildings are major contributors to energy consumption in Japan, largely due to increasing floor area and air conditioning demand. This highlights the importance of demand-side strategies for improving energy efficiency.

Demand response (DR) has been widely adopted as an effective approach to reduce or shift peak electricity demand. Studies in the United States and Europe show that DR can reduce peak loads by 2–10% and provide significant system flexibility (Albadi & El-Saadany, 2008; Gils, 2014).

1.2 CLT Buildings and Thermal Inertia

Cross-Laminated Timber (CLT) has gained attention as a low-carbon construction material supported by national policies promoting timber use. In addition to its environmental benefits, CLT exhibits moderate thermal inertia, which can improve indoor temperature stability and reduce HVAC demand.

Previous studies have shown that CLT buildings can achieve significant energy savings compared with conventional structures, while maintaining a balance between thermal performance and structural efficiency (Liu et al., 2016; Pépin et al., 2020). Compared to lightweight systems, CLT provides improved thermal buffering, although it does not reach the thermal mass of concrete structures.

1.3 Literature Review and Research Gap

Demand response strategies for HVAC systems, such as pre-cooling and temperature setpoint adjustment, have been shown to reduce peak loads and improve energy efficiency. Empirical studies indicate that demand response can reduce peak load by 2%–10% in U.S. wholesale markets, with even higher short-term reductions in some regions (Albadi & El-Saadany, 2008). In Europe, it provides tens of gigawatts of flexible capacity, reducing reliance on conventional peak generation (Gils, 2014). At the building level, the effectiveness of these strategies depends on the thermal characteristics of the building envelope, particularly thermal mass. Building thermal mass can reduce peak electricity demand by storing cooling during low-temperature periods and releasing it later, thereby delaying indoor temperature rise and shifting cooling loads (Balaras, 1996).

Various indicators, including attenuation and time delay, have been used to characterize thermal inertia. However, existing studies are largely based on simulations or aggregated data, with limited empirical evidence from real buildings. Moreover, most studies focus on heavyweight structures, while the dynamic thermal behavior of CLT buildings remains insufficiently explored. In particular, the dynamic thermal inertia of CLT buildings under real operational conditions remains insufficiently quantified.

1.4 Research Objectives

This study aims to: (1) quantify the dynamic thermal inertia of a CLT office building under winter and summer conditions, (2) evaluate its interaction with HVAC operation, and (3) assess its potential for energy efficiency and demand response applications.

2. Methodology

2.1 Field measurement location

The measurement site is located at the Advanced Wood Engineering Research Institute of the University of Kitakyushu in Fukuoka, Japan. The region belongs to the Pacific climate zone, characterized by humid summers and relatively mild winters. The geographical location of the measurement site is illustrated in **Figure 1**.

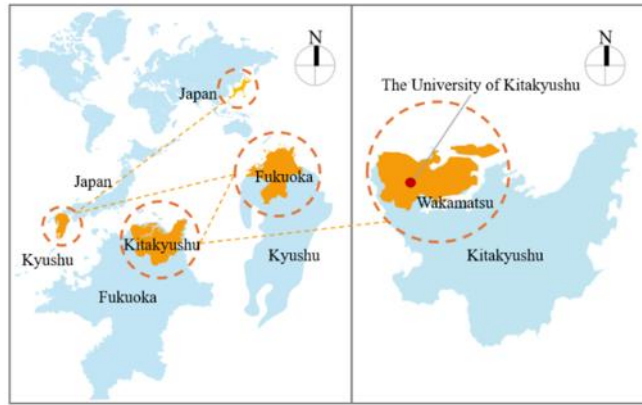


Figure 1. Experimental site.

2.2 Building Characteristics and Envelope

The building envelope consists of a 90 mm CLT panel, 20 mm phenolic foam insulation, and a 0.15 mm galvanized steel exterior layer, as illustrated in Figure 2 and detailed in Table 1.

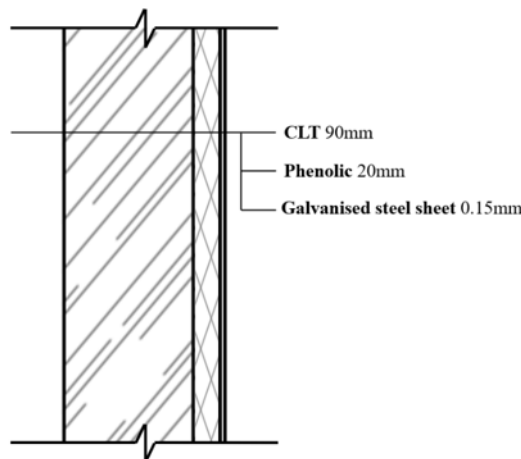


Figure 2. External Wall Structural Layers.

Table 1. Material properties of the building envelope

Material ID	Thickness(mm)	Conductivity(W/mK)	Specific Heat Capacity(J/kgK)	Density(kg/m ³)
CLT	90	0.097	2100	392
Phenolic	20	0.023	1400	30
Galvanized steel sheet	0.15	60	500	7850

2.3. Measurement System and Data Collection

Three measurement points were installed: two indoor points at heights of 0.75 m and 7 m, and one outdoor point on an external wall in a shaded and ventilated location. The layout is shown in Figure 3, Figure 4 presents the online monitoring interface, and Figure 5 illustrates the sensor device used in the study. Temperature and humidity were recorded using Ondotori data loggers (T&D Corporation, Japan). The building was operated under typical office conditions. Air conditioning was scheduled from 9:00 to 18:00, with a heating setpoint of approximately 22°C in winter and a cooling setpoint of approximately 26°C in summer. Occupancy followed standard office hours (9:00–

18:00), while natural ventilation was limited and shading conditions remained unchanged during the monitoring period. Data were recorded at 10-minute intervals and processed using temporal averaging.



Figure 3. Indoor measurement point layout in the CLT office building.



Figure 4. An Online monitoring platform showing real-time temperature and humidity data.



Figure 5. A temperature and humidity data logger used for field measurements.

2.4 Thermal Inertia Indicators and Data Robustness

To quantify thermal inertia, various evaluation metrics have been proposed. Givoni introduced the concept of “minimum building heat storage” under adiabatic conditions, linking it to improved night precooling effectiveness (Givoni, 1992). Building on this, Asan proposed the widely adopted indicators of time delay and attenuation factor, which were initially developed for steady-state envelope analysis and later extended to dynamic indoor temperature studies (Asan, 1998). Antonopoulos further introduced additional metrics, including effective heat capacity, time constant, and thermal lag, to describe overall building thermal dynamics (Antonopoulos, 1998).

Among these, the attenuation factor and time delay remain the most commonly used indicators and are therefore employed in this study to quantify thermal inertia.

(1) Attenuation coefficient (ν): Measures the reduction of temperature fluctuation amplitude:

$$\nu = \frac{A_{out}}{A_{in}}$$

$$A = T_{max} - T_{avg}$$

(2) Time delay (ξ): Represents the temperatures time lag between outdoor and indoor temperature peaks:

$$\xi = t_{in}^{max} - t_{out}^{max}$$

(3) Temperature decay index (α_{decay}): Represents the rate of indoor temperature change after HVAC shutdown:

$$\alpha_{decay} \approx \frac{T_{t2} - T_{t1}}{t_2 - t_1}$$

The analysis period was selected between 30 and 60 minutes after HVAC shutdown to reduce transient effects.

3. Results

3.1 Winter Conditions

3.1.1 Passive Response without HVAC

As shown in **Figure 6**, the CLT building maintained relatively stable indoor temperatures despite significant outdoor fluctuations during the winter monitoring period. During a five-day period without active heating, the calculated attenuation coefficient ($\nu = 6.16$) indicates strong dampening of external thermal variation by the building envelope. The phase lag time ($\xi = 2$ h 38 min) further demonstrates a delayed indoor thermal response, consistent with the moderate-to-high thermal inertia of mass timber systems. These characteristics are associated with the low thermal conductivity and heat storage capacity of CLT, which slow the transmission of external temperature variations into the indoor environment.

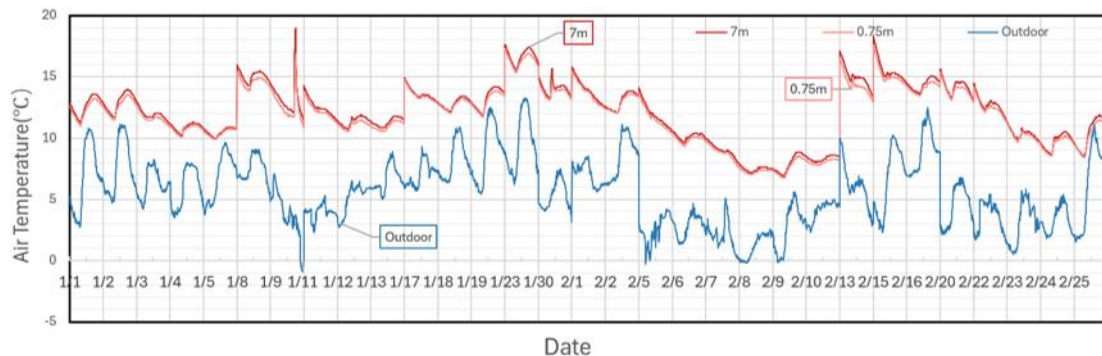


Figure 6. Indoor and outdoor temperatures at the monitoring site during winter (without air conditioning).

However, indoor temperatures remained consistently below 10°C, which is outside the thermal comfort range, indicating a limitation of passive thermal inertia in cold climates. While the building envelope effectively stabilizes temperature fluctuations, it does not provide sufficient heat retention in the absence of internal gains or solar input.

As shown in **Figure 7**, indoor relative humidity remained more stable than outdoors but consistently exceeded 70%.

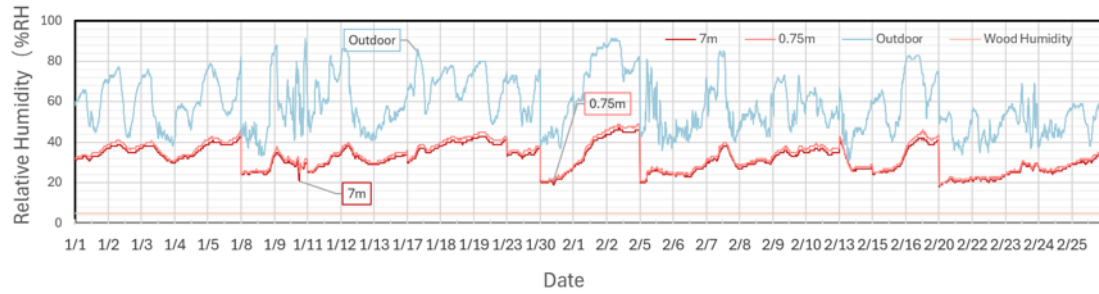


Figure 7. Indoor and outdoor humidity at the monitoring site during winter (without air conditioning).

This suggests a moisture buffering effect of the CLT material, while also indicating potential risks of condensation, particularly on colder surfaces or thermally bridged areas. Mild vertical stratification was observed between measurement heights, implying limited air mixing under passive conditions.

These results highlight the dual role of CLT passive performance: it effectively reduces environmental fluctuations but requires mechanical support to achieve acceptable indoor thermal comfort in winter conditions. Some high attenuation coefficient values may result from very small indoor temperature amplitudes and should be interpreted with caution. The calculated attenuation coefficients are summarized in **Table 2**.

Table 2. Attenuation coefficient under winter passive conditions

Date	Outdoor Amplitude (A_{out} °C)	Indoor Amplitude (A_{in} °C)	Attenuation Coefficient (ν)
1/1	3.9	0.9	0.565
1/2	3.5	1.1	0.461
1/3	1.9	0.1	19.000
1/4	1.9	0.4	4.000
1/5	2.7	0.4	6.750

The corresponding phase lag times are presented in **Table 3**.

Table 3. Phase lag time under winter passive conditions

Date	Indoor peak time (t_{in}^{max})	Outdoor peak time (t_{out}^{max})	Time lag ξ (h: min)
1/1	16:24	13:44	2:40
1/2	17:14	13:34	3:40
1/3	13:04	12:14	0:50
1/4	16:04	11:44	4:20
1/5	18:04	15:24	2:40

3.1.2 Response with HVAC

As shown in **Figure 8**, indoor temperatures increased rapidly from approximately 10°C to a stable range of 20–24°C during daytime occupancy after heating was activated, despite continued outdoor fluctuations. This indicates a stable interaction between CLT thermal inertia and HVAC operation, where the building envelope reduces external disturbances and supports a consistent indoor thermal environment.

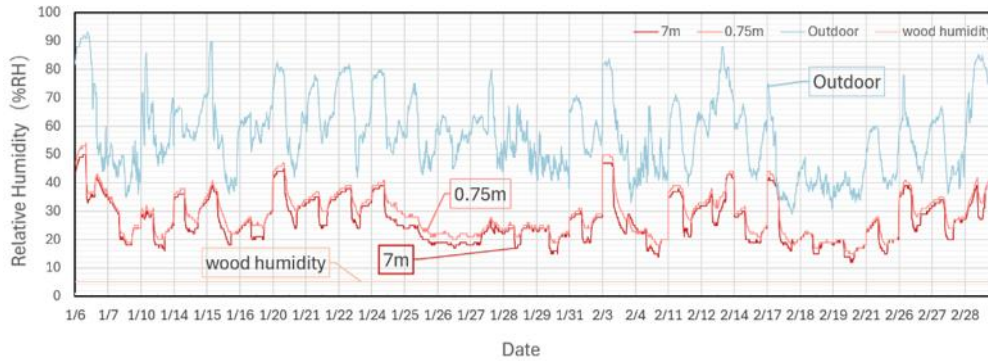


Figure 8. Indoor and outdoor temperatures at the monitoring site during winter.

As shown in **Figure 9**, indoor relative humidity decreased from values above 70% under passive conditions to approximately 40–50% with HVAC operation. This reflects effective dehumidification and reduced humidity fluctuation, resulting in improved indoor environmental stability.

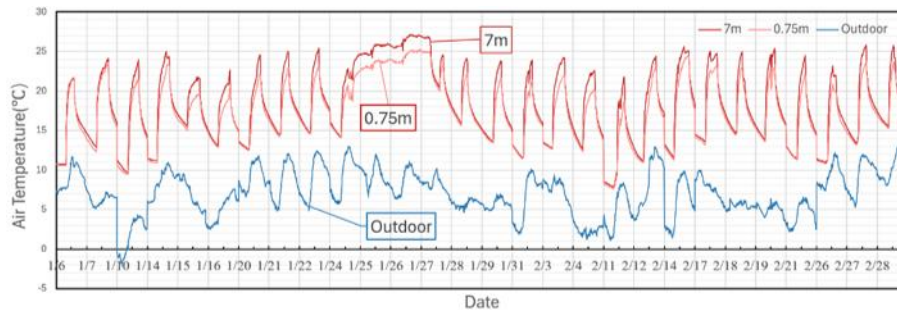


Figure 9. Indoor and outdoor humidity at the monitoring site during winter.

The temperature decay indices after HVAC shutdown are summarized in **Table 4**. The calculated value ($\alpha_{\text{decay}} = -0.0367$) indicates a gradual thermal response, meaning that indoor temperature declines slowly when heating stops. This behavior contributes to maintaining short-term thermal stability and reducing the frequency of HVAC cycling.

Table 4. Temperature decay index under winter air-conditioning conditions

Date	T2 (°C)	T1 (°C)	Δt (min)	α_{decay}
1/6	18	18.8	30	-0.027
1/7	19.7	21.2	30	-0.050
1/20	20.2	21.4	30	-0.040
1/21	20.5	21.5	30	-0.033
1/22	21.3	22.3	30	-0.033

Overall, the winter results indicate that CLT structures exhibit favorable thermal inertia properties. While passive performance alone is insufficient to ensure thermal comfort, it provides a stable foundation for efficient HVAC operation under winter conditions.

3.2 Summer Conditions

3.2.1 Passive Response without HVAC

As shown in **Figure 10**, indoor temperatures remained relatively stable compared to outdoor fluctuations during the summer monitoring period without air conditioning. Despite significant variations in outdoor temperature, indoor conditions exhibited reduced amplitude and smoother trends, indicating the buffering effect of the CLT building envelope.

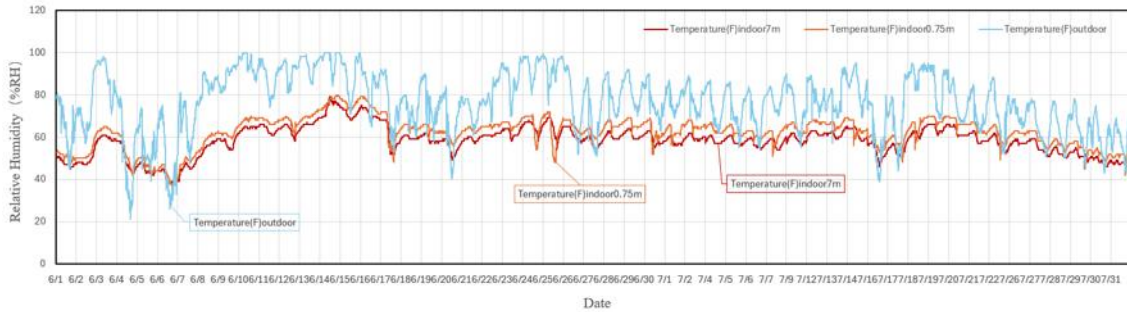


Figure 10. Indoor and outdoor temperatures at the monitoring site during summer (without air conditioning).

However, indoor temperatures remained consistently above the thermal comfort range, particularly during daytime periods, reflecting the limitation of passive thermal inertia under high-temperature conditions. While CLT reduces temperature fluctuations, it does not prevent heat accumulation in the absence of active cooling. As shown in **Figure 11**, indoor relative humidity remained more stable than outdoor conditions but generally stayed at elevated levels. This suggests that while the CLT structure provides some moisture buffering, it is insufficient to maintain indoor comfort under humid summer conditions.

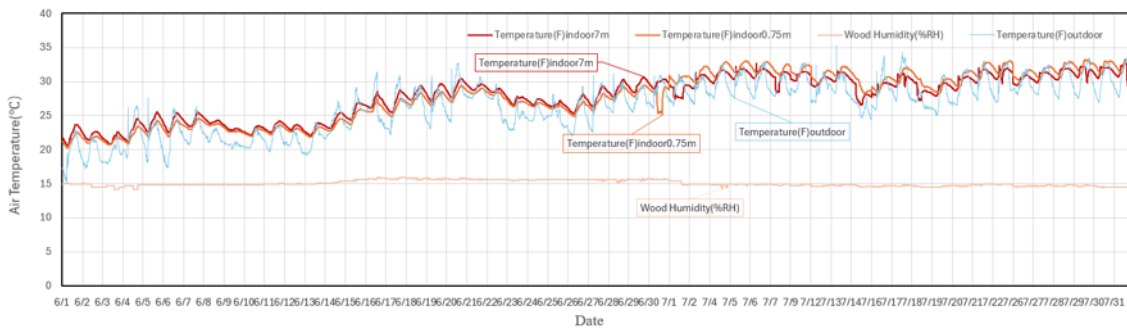


Figure 11. Indoor and outdoor humidity at the monitoring site during summer (without air conditioning).

These results indicate that, under passive conditions, CLT buildings can moderate environmental fluctuations but cannot ensure thermal comfort in hot and humid climates without mechanical cooling.

3.2.2 Response with HVAC

As shown in **Figure 12**, indoor temperatures remained within a relatively stable range under air-conditioning operation, despite continued outdoor fluctuations. Compared to passive conditions, temperature variations were significantly reduced, indicating effective regulation by the HVAC system in combination with the thermal inertia of the CLT structure.

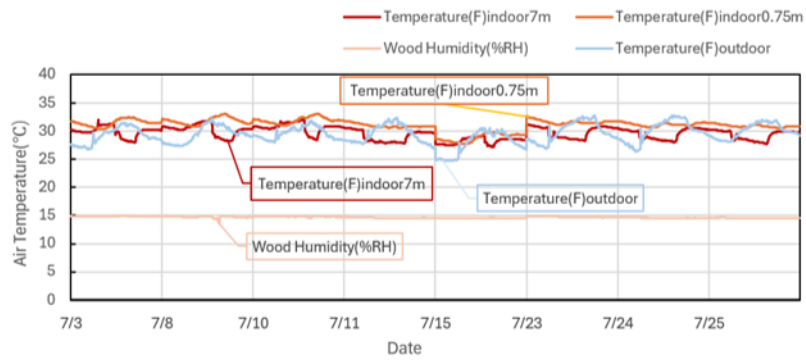


Figure 12. Indoor and outdoor temperatures at the monitoring site during summer.

As shown in Figure 13, indoor relative humidity decreased and remained more stable under HVAC operation compared to passive conditions. Although outdoor humidity levels fluctuated significantly, indoor conditions were maintained within a narrower range, demonstrating the effectiveness of mechanical dehumidification. This stabilization of indoor humidity also contributes to improved thermal comfort and reduces the risk of moisture-related issues such as condensation.

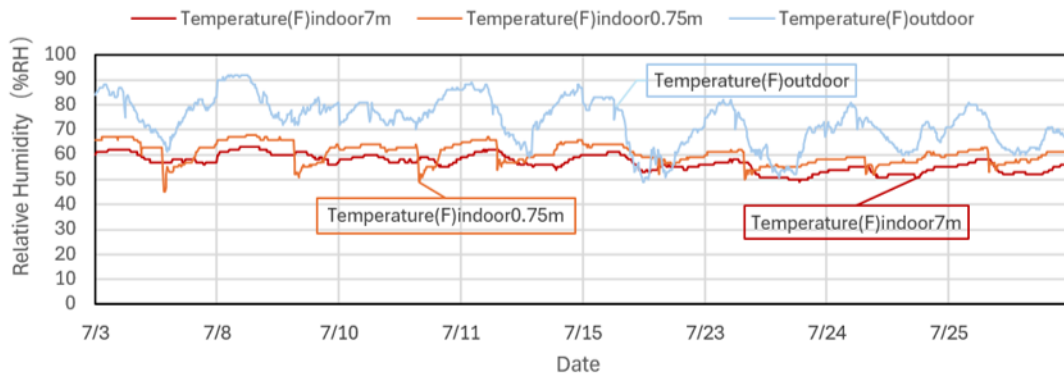


Figure 13. Indoor and outdoor humidity at the monitoring site during summer.

The temperature decay indices after HVAC shutdown are summarized in the corresponding table (consistent with the methodology described in Section 2). The results indicate a gradual indoor temperature response, suggesting that thermal inertia slows temperature variation after cooling is stopped, thereby contributing to short-term thermal stability and reducing peak cooling demand.

Overall, the summer results show that CLT buildings provide effective thermal buffering but require active cooling to maintain indoor comfort. When combined with HVAC operation, the thermal inertia of CLT contributes to improved environmental stability and more efficient system performance. This behavior also indicates the potential for reducing short-term peak cooling demand through optimized HVAC scheduling. The calculated temperature decay indices are summarized in Table 5.

Table 5. Temperature decay index under summer air-conditioning conditions.

Date	T2 (°C)	T1 (°C)	Δt (min)	α_{decay}
7/3	29.7	29.2	30	0.017
7/8	29.8	29.3	30	0.017
7/10	30.3	29.8	30	0.017
7/11	29.4	28.9	30	0.017
7/15	28.2	27.8	30	0.013

4. Discussion

The results demonstrate a clear interaction between the thermal inertia of CLT buildings and HVAC operation, contributing to a more stable indoor thermal environment and reduced temperature fluctuations across seasons. The observed attenuation and time-delay effects are consistent with established theories of dynamic thermal response in building envelopes, where thermal mass moderates external temperature variations through damping and phase-shifting mechanisms (Balaras, 1996; Antonopoulos, 1998). Although CLT structures are generally classified as moderate thermal mass systems compared to heavyweight constructions, previous studies have shown that they can still provide meaningful thermal buffering under real operating conditions. Comparative analyses across materials further indicate that concrete structures provide the strongest thermal buffering, while timber-based systems offer an intermediate balance between thermal inertia, energy efficiency, and indoor comfort (Pépin et al., 2020). The present findings further support this understanding by providing empirical evidence from a monitored office building.

From a demand response perspective, the moderate thermal inertia of CLT enables a certain degree of flexibility in HVAC operation without compromising indoor thermal comfort. The observed delayed thermal response and gradual temperature decay are particularly relevant for strategies such as pre-cooling and delayed heating, which have been widely discussed as effective approaches for load shifting in buildings with thermal storage capacity (Klaassen, 2002; Braun, 2006). These strategies can reduce peak electricity demand and enhance load flexibility, contributing to more efficient interaction with energy systems (Jurjevic & Zakula, 2023). The results of this study are in line with previous research on the use of building thermal mass for demand-side management, while extending the evidence base by demonstrating these effects in a CLT office building under real operational conditions.

From a practical standpoint, the results highlight the potential of CLT as a low-carbon building material that supports energy-efficient and climate-responsive design. In addition to its reduced embodied carbon compared to conventional materials, timber-based construction has been increasingly recognized for its role in sustainable building development (Pépin et al., 2020). In cold regions of China, Liu et al. reported that, over a 50-year life cycle, CLT residential buildings achieved energy savings of 32.3%–36.4% and carbon emission reductions of 42.9%–45% compared with reinforced concrete buildings, assuming a 55% material recycling rate (Liu et al., 2016). When combined with appropriate HVAC control strategies, the passive thermal buffering capacity of CLT can contribute to improved operational energy performance and facilitate more flexible building-to-grid interactions (Jurjevic & Zakula, 2023; Todorean et al., 2025). This integrated approach aligns with current trends toward low-carbon and smart energy systems in the built environment.

However, the generalizability of the findings is limited by the relatively short monitoring period and the use of a single building case. In addition, factors such as internal heat gains, occupant behavior, and envelope variability may influence the observed thermal performance and introduce uncertainties into the analysis. Future research should therefore incorporate longer-term monitoring, multiple building types, and uncertainty analysis methods to further validate and extend the applicability of the results.

5. Conclusion

This study demonstrates that CLT office buildings exhibit strong thermal inertia and stable seasonal thermal performance. The results confirm that CLT structures can effectively buffer external temperature fluctuations and maintain a stable indoor environment when combined with HVAC operation, supporting energy-efficient climate control. From a practical perspective, the findings highlight the compatibility between CLT thermal behavior and mechanical systems, aligning with the passive building principle of combining natural regulation with active control (Braun, 2006). The observed thermal response characteristics indicate the potential for optimizing HVAC operation strategies, particularly in improving load stability and reducing short-term energy demand (Klaassen, 2002).

Scientifically, this study contributes empirical evidence on the dynamic thermal performance of CLT buildings based on in-situ monitoring under real operating conditions. The results provide a foundation for developing climate-responsive control strategies and integrating CLT buildings into energy-efficient and grid-interactive building systems (Todorean et al., 2025). Future research should focus on integrating physical and data-driven models to

further optimize HVAC control strategies and improve the energy performance and resilience of CLT buildings across different climates and building types.

6. Limitations and Future Outlook

This study provides foundational insights into the thermal inertia of CLT buildings and their interaction with HVAC operation; however, several limitations remain. The monitoring period was relatively short and limited to a single office building, constraining the generalizability of results across building types, climates, and usage patterns.

Although thermal inertia parameters (v , ξ , α_{decay}) were successfully quantified, specific HVAC control strategies were not developed—indicating the need for future work in predictive model construction and simulation-based control testing. Furthermore, the current analysis primarily focused on energy performance, with less emphasis on how thermal inertia affects perceived thermal comfort, such as indoor temperature stability and mean radiant temperature. A more interdisciplinary approach, integrating building physics, materials science, and control engineering, will be essential to bridge performance metrics with occupant experience. Lastly, the study did not incorporate formal uncertainty analysis; future work should apply sensitivity testing and probabilistic methods to improve the robustness and applicability of thermal performance models under real-world conditions.

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Ethics approval

Not applicable.

Conflict of interest

The authors declare that there is no competing interest.

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