EPiC Series in Built Environment

Volume 7, 2026, Pages 1142–1151

Proceedings of Associated Schools of Construction 62nd Annual International Conference

Comparative Thermal Performance Analysis of Cross-laminated Timber (CLT) Exterior Walls under Varying Insulation Configurations and Climatic Conditions in the Northeastern United States

Shay Kurzinski [1], Pouria Mahdaviani[2], Ellis Hwang[1], Carson Boswell[1], Shayan Mirzabeigi [2,3]
[1]Roger Williams University, [2]Syracuse University. [3]State University of New York College of Environmental Science and Forestry (SUNY ESF).

Cross-laminated timber (CLT) is increasingly adopted for sustainable building construction; however, the energy and durability performance of CLT wall systems strongly depend on insulation configuration and climate. This study compared performance of three CLT wall assemblies including exterior-insulated, split-insulated, and interior-insulated, under two northeastern climate zones of Bristol, Rhode Island (4A) and Syracuse, New York (5A). Using the Combined Heat, Air, and Moisture–Building Envelope Systems (CHAMPS-BES) software, steady-state simulations were conducted to evaluate temperature distribution, heat flux, and thermal conductance through each configuration. Results show that insulation placement considerably alters thermal continuity and the temperature stability of the CLT layer. The split-insulated assembly achieved the lowest thermal conductance (0.14 $W/m^2 \cdot °C$) and the most uniform temperature profile in both climates, while the exterior-insulated system performed comparably well in the milder coastal environment. The interior-insulated wall produced the steepest gradients and highest conductance, reflecting lower efficiency. Although overall behavior remained consistent, greater temperature differentials in Syracuse amplified heat-flow magnitude. Findings indicate that insulation strategy should align with regional climate and envelope design intent, as hybrid and exterior-insulated walls enhance thermal performance and potential durability.

Keywords: Cross-Laminated Timber (CLT); Thermal Performance; Insulation Placement; Building Envelope; Energy Efficiency.

Introduction

Cross-Laminated Timber (CLT) is recognized as a sustainable structural material that integrates renewable sourcing with high mechanical strength and dimensional stability (Kurzinski et al., 2022). Its carbon sequestration capacity and rapid construction are notable advantages that have driven adoption across building applications. While CLT has been traditionally employed in roof and floor assemblies, its use in exterior wall systems is expanding rapidly following the adoption of tall mass timber provisions in the 2021 International Building Code (IBC), particularly for mid- and high-rise construction where thermal and moisture performance become critical design considerations. The performance of CLT buildings is determined by the effectiveness of wall assemblies in managing both heat and moisture transfer. In cold-humid conditions, inadequate moisture control can result in condensation, mold growth, or material degradation, even when walls possess high thermal resistance (Kurzinski et al., 2025). However, the comparative influence of insulation placement strategies on CLT wall performance across diverse climates remains insufficiently characterized. As a result, recent research increasingly explored how insulation type, vapor control strategies, and wall layering collectively affect the thermal and moisture performance of CLT assemblies. Experimental studies indicate that both material selection and assembly configuration considerably influence performance outcomes (Mirzabeigi et al., 2023). Controlled tests of CLT wall panels with bio-based fiber insulation under cyclic humidity and temperature conditions showed that wood fiber functions as a hygroscopic buffer, moderating humidity fluctuations, and delaying vapor migration. The addition of air barriers stabilized temperature gradients but reduced material recyclability at the end of life (De Serres-Lafontaine et al., 2024). Field monitoring of double-stud wood walls at the Kern Center in Amherst, Massachusetts, demonstrated that cellulose insulation-maintained wood moisture content below 20 percent, the threshold for decay, and achieved R-values above 40 when combined with smart vapor membranes (Picciotto et al., 2023). Additional research underscores the importance of vapor permeability. O'Brien et al. (O'Brien et al., 2025) conducted field monitoring and modeling of a CLT and wood fiber-insulated building in a cold climate (Zone 6A) in Belfast, Maine. The results showed that vapor-open wall assemblies are highly affected by interior environmental conditions, highlighting the necessity of accounting for interior humidity and temperature in CLT assembly design. Reviews of high-performance wall systems support these observations, indicating that R-values above 40 can be achieved with double-stud walls, structural insulated panels (SIPs), or CLT composites. However, increased cost and construction complexity remain significant barriers (Kosny et al., 2014). Salonvaara and Desjarlais. (Salonvaara & Desjarlais, 2024) also found that embedding insulation within CLT layers, rather than applying it externally, improved thermal performance by approximately seven percent and reduced annual energy use by two to three percent. These results emphasize that insulation placement has a measurable impact on energy performance. Modeling using probabilistic methods have enhanced the understanding of moisture dynamics under variable boundary conditions. Wang and Ge (Wang & Ge, 2016) showed that CLT wall assemblies with low-permeance water-resistive barriers retain higher internal moisture and exhibit slower drying rates than vapor-open systems, which increases the risk of moisture accumulation in humid climates. Park et al (Park et al., 2025) expanded on this by evaluating ply-lam CLT assemblies in a dry-winter, humid-continental climate, finding that condensation and mold risks vary significantly with cladding type, insulation thickness, and joint detailing. These findings highlight the necessity of climate-specific envelope design. Parallel studies in extreme cold regions provide additional insight. Palani et al. (Palani et al., 2023) analyzed wall assemblies optimized for subarctic conditions, finding that even thermally robust designs can develop mold risk if vapor diffusion and drying potential are constrained. The U.S. Department of Energy's Oak Ridge National Laboratory (Salonvaara et al., 2025) recently expanded empirical evidence by evaluating the energy, hygrothermal, and thermal-capacity performance of CLT wall assemblies in U.S. climates, documenting how envelope detailing, particularly continuity of insulation and membrane selection, affects both seasonal heat storage and moisture buffering. Validation and sensitivity analyses of CLT assemblies with continuous exterior insulation further indicate potential heating-energy reductions up to 23% and cooling-load decreases 18% when thermal continuity is improved (Flechas et al., 2025). Although these studies collectively strengthen knowledge of CLT wall behavior, a critical gap remains: most investigations isolate individual parameters such as insulation material, embedded layers, or membrane type, without systematically comparing insulation placement strategies—exterior, split, and interior configurations—within a consistent framework or across different climatic contexts. Consequently, design practitioners lack comparative performance data to inform insulation placement decisions for CLT buildings in cold-humid northeastern climates. Moreover, few studies directly evaluate these strategies in northeastern U.S. climates, where moisture and temperature loads differ sharply between coastal and inland regions.

To address this gap, this study objective is to systematically compare the thermal and hygrothermal performance of three CLT wall assemblies—exterior-insulated, split-insulated, and interior-insulated—through simulation and data analysis. Bristol, Rhode Island (Zone 4A, coastal) and Syracuse, New York (Zone 5A, inland) were selected as representative extremes that bracket the predominant northeastern cold-humid climate conditions. Bristol is a coastal site characterized by high humidity and marine air exposure, while Syracuse is known for prolonged freeze cycles and lake-effect snow. Together, these locations capture the key thermal and moisture gradients relevant to CLT wall design in this region. The findings aim to inform design strategies for durable, energy-efficient CLT building envelopes tailored to diverse cold-humid conditions in the northeastern United States.

Methodology

The present study employed a model-based evaluation approach to assess how insulation placement influences the hygrothermal and thermal behavior of CLT wall assemblies under the climatic conditions of the northeastern United States. Three wall configurations—exterior-insulated, split-insulated, and interior-insulated assemblies—were modeled to isolate the effects of insulation position while maintaining consistent materials, cladding, and boundary conditions across all cases. The research focused on two representative climatic zones: Bristol, Rhode Island (Climate Zone 4A, cold-humid coastal), and Syracuse, New York (Climate Zone 5A, cold-humid inland). These locations were chosen for their contrasting temperature ranges, relative humidity levels, and moisture exposure patterns, which together represent the performance envelope of CLT-based construction in the region.

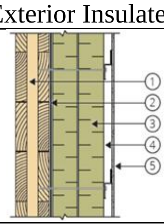
Wall Assembly Configurations

Each wall assembly was modeled as a one-dimensional vertical cross-section through the building envelope to capture the dominant direction of heat and moisture transport.

Exterior Insulated Assembly

This configuration places the insulation on the exterior side of the CLT panel. The mass timber acts as the primary structural element, while the continuous exterior insulation reduces thermal bridging and enhances overall energy efficiency. The air and water-resistive barrier protect the CLT from moisture, and the ventilated and drained air cavity behind the cladding allows for drying and moisture control. This assembly is common for cold climates due to its superior thermal performance and durability.

Table 1. Exterior Insulated Wall Details (Modified Adoption from RDH Building Science, 2022)

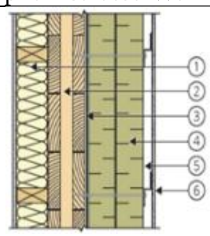


1.	Gypsum Board (interior finish)
2.	Mass Timber Panel
3.	Air Barrier and Water-Resistive Barrier
4.	Exterior Insulation
5.	Ventilated and drained air cavity
6.	Cladding

Split Insulated Assembly

In this hybrid system, insulation is divided between the interior and exterior sides of the CLT panel. The CLT remains near the thermal center of the wall, balancing heat storage and insulation. The air and water-resistive barrier protect the assembly, while the exterior insulation and ventilated cavity further prevent condensation and moisture buildup. This approach improves thermal performance by positioning the CLT within a more moderate temperature zone, reducing freeze-thaw cycling and enhancing the panel's role as a thermal buffer.

Table 2. Split Insulated Wall Details (Modified Adoption from RDH Building Science, 2022)

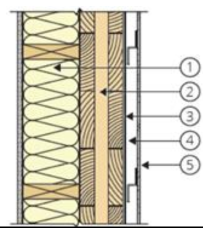


1. Gypsum Board (interior finish)
2. Interior Insulation
3. Mass Timber Panel
4. Air Barrier and Water-Resistive Barrier
5. Exterior Insulation
6. Ventilated and drained air cavity
7. Cladding

Interior-Insulated Assembly

On this assembly, all insulation is located on the interior side of the CLT panel. The panel is fully within the conditioned space, which allows for an exposed wood aesthetic and use of its thermal mass to regulate interior temperature swings. Due to the insulation being located on the interior, the exterior layers (air barrier, cavity, cladding) must effectively protect the CLT from external moisture and temperature fluctuations. Compared to two other scenarios, this assembly can be less efficient in terms of managing condensation.

Table 3. Interior-Insulated Assembly Details (Modified Adoption from RDH Building Science, 2022)



1. Gypsum Board (interior finish)
2. Interior Insulation
3. Mass Timber Panel
4. Air Barrier and Water-Resistive Barrier
5. Ventilated and drained air cavity
6. Cladding

Hygrothermal Simulations and Material Properties

The thermal characteristics of each material layer were defined through a combination of literature review, standardized databases, and manufacturer of technical data sheets. Key parameters included thermal conductivity, specific heat capacity, bulk density, vapor diffusion resistance (μ-factor), and moisture storage functions. For hygroscopic materials such as wood fiber insulation and CLT, sorption isotherms and liquid transport coefficients were input as tabulated functions, allowing accurate representation of moisture buffering and capillary behavior. Where manufacturer's data were incomplete, values were interpolated using linear interpolation from published sources for comparable products and verified against typical values in the material databases of the modeling software. These inputs collectively formed the material characteristics matrix applied to each layer in the assemblies.

Table 4. Thermal Properties of Layers in the Wall Assemblies

Layer Description	Material Type	Thickness (mm)	Thermal Conductivity (W/mK)	Heat Capacity (J/KgK)	Density (Kg/m^3)	R-Values (m^2·K / W)
Gypsum Board (interior)	Gypsum board	12	0.199	849.9	849.96	0.34
Weather / Vapor Barrier	Polyethylene	0.1	0.04	1400	900	0.17
Interior Insulation	Wool	100	0.042	1400.06	154.99	13.51

Mass Timber Panel	Softwood	83.3	0.119	1400.06	453.98	3.95
Exterior Insulation	Gutex Multitherm	152.5	0.039	2101.77	139.99	21.67
Air Cavity	Air	19	0.179	999.80	1.30	0.60
Cladding	Cement Board	12.7	0.097	1300.00	410.06	0.74

Modeling Framework and Governing Equations

Combined Heat, Air, Moisture, and Pollutant Simulation–Building Envelope Systems (CHAMPS-BES) is a software that combines heat and moisture transfer through wall assemblies. This software basically employs the well-known Delphin 5 numerical engine for steady state and transient hygrothermal simulation (Mirzabeigi et al., 2025). This framework solves the nonlinear partial differential equations for conservation of energy (equation 1) and moisture (equation 2) within a porous medium. The governing heat transfer equation expresses the rate of change of internal energy as a function of heat conduction, vapor transport, and latent heat effects, while the moisture balance equation accounts for both liquid and vapor diffusion processes. It should be noted that in our current study, our problem was confined to solving the energy equation 1, while the only effective term on the right-hand side is the heat conduction through the solid. These equations are represented in the following as:

$$\frac{\partial \rho^{U}}{\partial t} = -\frac{\partial}{\partial x}\left(\mu j^{v}_{conv} + j^{Q}_{diff} + h j^{v}_{diff}\right) + \sigma^{U}_{ref} \quad (1)$$

$$\frac{\partial \rho^{m_{w+v}}}{\partial t} = -\frac{\partial}{\partial x}\left(j^{mw}_{conv} + j^{mv}_{conv} + j^{mv}_{diff}\right) + \sigma^{mw+v}_{ref} \quad (2)$$

where ρ^{U} = internal energy density, J/m^3, μ = specific internal energy, J/kg, j^{v}_{conv} = convective water vapor flux, kg/(m^{2}s), j^{Q}_{diff} = heat conduction, J/(m^{2}s), h = specific of water vapor in J/kg, σ^{U}_{ref} = energy sources/sinks, J/m^{3}s, $\rho^{m_{w+v}}$ = moisture density, kg/m^3, j^{mw}_{conv} = convective liquid (capillary) water flux, kg/(m^{2}s), j^{mv}_{conv} = convective water vapor flux, kg/(m^{2}s), j^{mv}_{diff} = diffusive water vapor flux, kg/(m^{2}s, σ^{mw+v}_{ref} = moisture sources/sinks in reference volume, kg/(m^{3}s).

Simulation Configuration and Boundary Conditions

Each wall was discretized into a series of nonuniform finite elements aligned with material interfaces. Fine discretization was applied near thin layers such as membranes and coatings to capture steep gradients in temperature. Spatial and temporal convergence tests confirmed that further refinement produced negligible change in the computed heat flux and interface moisture content. Boundary conditions were established to represent both steady-state climatic loads (heating and cooling design conditions). For steady-state simulation, indoor conditions were fixed at 21°C and 25% relative humidity during winter and 24°C and 50% relative humidity during summer for both Syracuse and Bristol. Based on the ASHRAE Handbook of Fundamentals (ASHRAE, 2021) and data from the National Oceanic and Atmospheric Administration (NOAA) Climate Normals Database (NOAA, 2020), outdoor conditions at Syracuse were specified by −16.7°C with 80% relative humidity for winter and 30°C with 70% relative humidity for summer, representing design extremes for cold-humid northeastern climates. At Bristol, outdoor conditions were defined as −12.5°C with 78% relative humidity for winter and 32°C with 65% relative humidity for summer Initial temperature and humidity fields were uniform within the wall, set to 0°C and 55% relative humidity for winter and 22°C and 55% for summer scenarios. Verification of the hygrothermal models was carried out through mesh and timestep convergence testing to ensure numerical stability. Conservation of mass and energy was verified by confirming that the net accumulation within the computational domain matched boundary inflows and outflows within acceptable tolerances. To provide a measure of external validity, simulated R-values and transient response behaviors were compared qualitatively against published hygrothermal studies of CLT assemblies (Salonvaara et al., 2025), (Wang & Ge, 2016), confirming that the magnitude and phase shift of thermal response fell within expected ranges.

Results and Discussion

Figure 1, 2, and 3 present the temperature distribution across the layers of the three wall assembly configurations under both winter and summer conditions for Bristol, RI, and Syracuse, NY. While similar temperatures were used for interior conditions in both cities, the difference in outdoor temperatures distinguishes between them in winter and summer.

In the split insulated assembly, the CLT layer remained above freezing in winter for both cities, demonstrating strong protection from exterior cold loads. In Syracuse's harsher climate, for example, the temperature within the CLT layer stabilized near 8.1 °C even as the exterior dropped below −15 °C. This shows effective thermal buffering by the dual insulation layers, minimizing temperature induced moisture risk. By contrast, the interior insulated assembly allowed the CLT layer to reach −14.1 °C, revealing a direct exposure to exterior cold that heightens condensation potential on the cold-side interface. Following on the simulations by changing the current thermal conductivity of show that if the interior-insulation thermal conductivity is increased from 0.042 to 0.0756 W/m·K for Bristol, RI, and to 0.105 W/m·K for Syracuse, NY, the temperature at the CLT's interior edge (start of the CLT layer) rises above 0 °C. These mean about 80% and 150% increase in the thermal conductivity respectively. In other words, higher conductivity, which reflects a lower R for the same thickness, allows more room-side heat to reach the CLT and mitigates subfreezing conditions at that interface.

During summer simulations, all assemblies maintained stable gradients; however, the exterior insulated wall demonstrated the lowest interior side temperature rise, indicating superior resistance to exterior heat gain and reduced risk of inward vapor drive. These results suggest that placement of insulation critically determines the extent of thermal stability across the CLT panel.

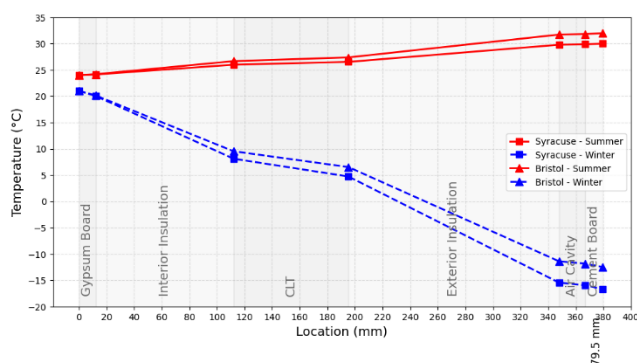


Figure 1. Temperature Profile Across Wall Layers – Split Insulated Wall Assembly

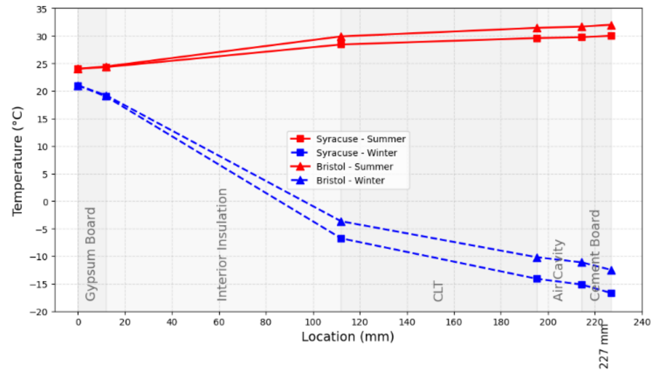


Figure 2. Temperature Profile Across Wall Layers – Interior Insulated Wall Assembly

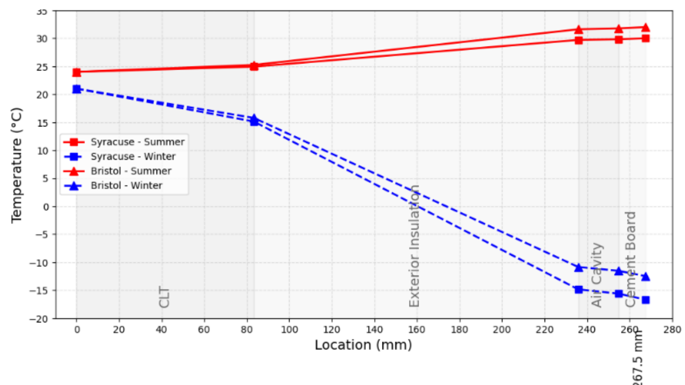
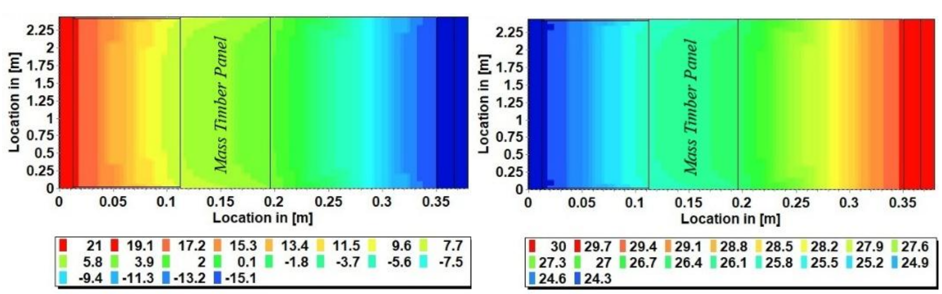


Figure 3. Temperature Profile Across Wall Layers – Exterior Insulated Wall Assembly

Temperature distribution over different layers of wall assembly systems was shown and discussed for cities of Syracuse and Bristol in Winter and Summer conditions. This can be observed in Figure 4 as well, where the contours of temperature for the split insulation system are shown for both summer and winter conditions at Syracuse. This figure also shown that these two-layer insulations maintained the Mass Timber Panel (CLT) layer temperature at a well above freezing situation, and it effectively protects this layer from moisture issues and extreme cold situations. However, as was mentioned before, this was not the case in the interior insulation assembly, where the CLT layer was exposed to a temperature as low as -14.10°C.



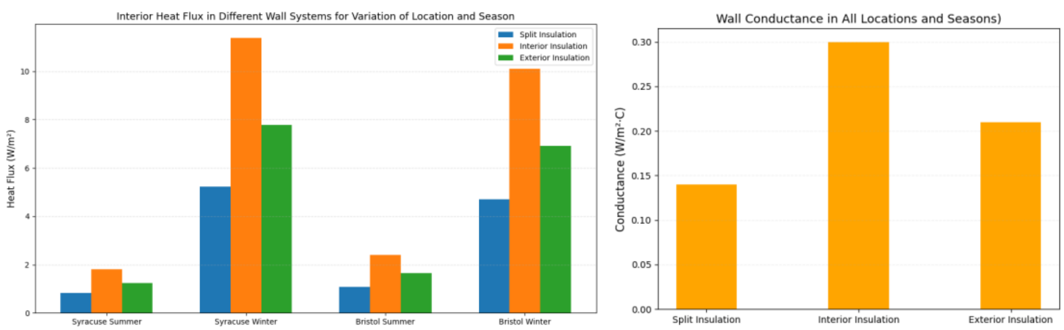
(a) (b)

Figure 4. Temperature contours for a split insulated assembly at Syracuse in (a) winter and (b) summer conditions.

As depicted in Figure 5a, heat flux magnitudes were substantially higher in winter than in summer for all wall systems, consistent with greater interior exterior temperature differentials. The interior insulated assembly produced the highest winter heat flux, while the split insulated system exhibited the lowest, confirming the advantage of combining interior and exterior insulation layers.

Figure 5b quantifies the conductance values of 0.30 W/m²·°C for interior insulated, 0.21 W/m²·°C for exterior insulated, and 0.14 W/m²·°C for split insulated assemblies. Although all three wall assemblies contain the same nominal insulation materials, the location of the insulation strongly influences the effective thermal conductance. When the insulation is placed on the interior, the heavy Mass Timber (CLT) panel is exposed to the exterior environment and becomes part of the cold-side thermal path. This reduces the thermal resistance because the CLT is significantly more conductive than the insulation. In contrast, exterior insulation thermally isolates the CLT and keeps it closer to the indoor temperature and this increases the overall resistance.

The split-insulation configuration provides the lowest conductance because both sides of the CLT are partially insulated, minimizing thermal bridges and creating a more uniform temperature gradient across the wall. As a result, the CLT acts as a protected thermal mass rather than an exposed conductive layer, which explains the factor-of-two reduction in effective conductance observed in Figure 5b.



(a) (b)

Figure 5. (a) Heat Flux (W/m2) from the simulations over different wall assemblies for both cities and weather conditions (b) Calculated conductance (W/m2°C) for different wall assemblies

The performance of each wall configuration varied with climatic conditions but followed a consistent thermal trend across both locations. In Bristol, characterized by milder winters and warmer, humid summers, the exterior-insulated and split-insulated assemblies maintained smoother temperature gradients and lower heat-flux values, indicating stronger resistance to outdoor temperature swings. The exterior insulation layer effectively reduced heat gain from elevated summer temperatures, while the split configuration distributed the temperature change more evenly across the section, keeping the CLT layer close to interior conditions. In Syracuse, where prolonged cold periods and greater temperature differentials dominate, the split-insulated assembly achieved the most uniform temperature profile through the wall and the lowest thermal conductance, confirming its efficiency in cold-humid inland climates. The interior-insulated configuration, by contrast, showed the steepest temperature gradients and the highest conductance, reflecting direct exposure of the CLT to exterior cold and reduced heat transfer from the interior side. These differences were evident in both the temperature plots and bar charts of heat flux and conductance, where the split system consistently demonstrated the smallest magnitude of thermal loss. Although the overall behavior pattern remained similar in both climates, the intensity of gradients increased in Syracuse due to its larger indoor–outdoor temperature differential. These results confirm that insulation placement influences heat transfer within CLT wall systems, and that climatic boundary conditions primarily amplify, rather than alter, relative performance among configurations.

Current Study Limitations and Future Work

The current numerical studies were confined to steady-state simulations to establish a baseline thermal performance and to calculate nominal R-values and thermal conductance for each configuration. These cases also serve to identify potential condensation zones at the CLT–insulation interface. In addition, the modeling adopted several simplifying assumptions consistent with prior hygrothermal research. Heat and moisture transfer were assumed one-dimensional, neglecting lateral effects such as thermal bridging at corners, openings, or fasteners. Material properties were treated as homogeneous within each layer, and construction imperfections such as gaps or discontinuities. Additionally, the current analysis employed fixed configurations for each insulation placement strategy and did not explore parametric variations within each wall type, such as insulation thickness ratios, membrane permeance levels, or alternative insulation materials, which may influence thermal and moisture performance. Future work will include sensitivity analyses to evaluate how these intra-type variations affect wall assembly behavior across different climate zones. Furthermore, the two selected climate locations represent contrasting boundary conditions within the northeastern cold-humid envelope, future work should expand the analysis to include additional ASHRAE climate zones (e.g., 3A, 6A, 7) to provide more comprehensive regional coverage. For the future work, it is proposed to conduct steady state as well as full-year transient simulations for both climatic locations, recording hourly profiles of temperature, relative humidity, and moisture content through the assembly. These transient simulations use hourly Typical Meteorological Year (TMY3) weather data for Bristol and Syracuse, including outdoor temperature, relative humidity, wind-driven rain, and solar radiation. Convective heat and mass transfer coefficients for both interior and exterior surfaces can be calculated as per ASHRAE Standard 160 and might be adjusted dynamically according to local wind speed. Parametric sensitivity analyses can also evaluate the influence of key design and material parameters, including insulation thickness, vapor permeability of the weather- or vapor- resistant barriers. In addition, energy simulations with software such as Energy Plus can be performed to validate the hygrothermal results directly, as they provide a comparative framework for assessing the broader energy implications of insulation placement strategies.

Conclusion

This study evaluated the influence of insulation placement on the steady-state thermal performance of CLT wall assemblies under two contrasting northeastern climates: Bristol, Rhode Island (coastal, mixed-humid), and Syracuse, New York (cold-humid inland). The simulations confirmed that insulation position has a measurable impact on heat transfer and temperature distribution within the wall section. Among the three configurations, the split-insulated system demonstrated the most stable temperature profile and lowest thermal conductance across both climates, indicating that distributing insulation on both sides of the CLT improves thermal continuity and heat-storage balance. The exterior-insulated wall also showed favorable results, particularly for coastal conditions where minimizing exterior heat gain and maintaining stable interior temperatures are priorities. In contrast, the interior-insulated system showed steeper temperature gradients and higher heat flux. This configuration is thermally less effective because the CLT layer becomes part of the cold-side thermal path. For CLT buildings in the northeastern United States, hybrid (split) and exterior-insulated envelopes offer greater thermal efficiency and durability potential, especially when paired with proper vapor control and drainage detailing. While the present analysis focused on steady-state thermal behavior, future work will integrate transient hygrothermal simulations and field monitoring to evaluate moisture-content trends and assess long-term durability risks. These next steps will provide a more comprehensive understanding of how insulation configuration affects both the energy and hygrothermal performance of CLT building envelopes in new construction and retrofit applications.

References

ANSI/ASHRAE. (2024). ANSI/ASHRAE/IES Standard 90.1-2022: Energy Savings Analysis (90.1). U.S. Department of Energy. https://www.ashrae.org/technical-resources/bookstore/standard-90-1

ASHRAE. (2021). ASHRAE Handbook—Fundamentals (SI ed.). American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

De Serres-Lafontaine, C., Blanchet, P., Charron, S., Delem, L., & Wastiels, L. (2024). Bio-based innovations in cross-laminated timber (CLT) envelopes: A hygrothermal and life cycle analysis (LCA) study. Building and Environment, 256, 111499. https://doi.org/10.1016/j.buildenv.2024.111499

Flechas, G. M., Salonvaara, M., & Tabares-Velasco, P. C. (2025). Validation and moisture content sensitivity analysis of cross-laminated timber wall assemblies in EnergyPlus. Journal of Building Engineering, 108, 112852. https://doi.org/10.1016/j.jobe.2025.112852

Kosny, J., Asiz, A., Smith, I., Shrestha, S., & Fallahi, A. (2014). A review of high R-value wood framed and composite wood wall technologies using advanced insulation techniques. Energy and Buildings, 72, 441–456. https://doi.org/10.1016/j.enbuild.2014.01.004

Kurzinski, S., Crovella, P., & Kremer, P. (2022). Overview of cross-laminated timber (CLT) and timber structure standards across the world. Mass Timber Construction Journal, 5(1), 15–27.*

Kurzinski, S., Mirzabeigi, S., & Riccitelli, B. (2025). Comparative performance analysis of mass timber, conventional, and SIPs envelope systems in residential buildings. Mass Timber Construction Journal, 8(1), 42–55.*

Mirzabeigi, S., Zhang, J., & Razkenari, M. (2023). Exterior retrofitting systems for energy conservation and efficiency in cold climates: A systematic review. In L. L. Wang et al. (Eds.), Proceedings of the 5th International Conference on Building Energy and Environment (COBEE 2022), Environmental Science and Engineering. Springer, Singapore. https://doi.org/10.1007/978-981-19-9822-5_44

Mirzabeigi, S., Zhang, R., Krietemeyer, B., & Zhang, J. (2025). Modeling the effects of panel interfaces on air-tightness and thermal performance of an integrated whole-building energy efficiency retrofit assembly. In U. Berardi (Ed.), Multiphysics and Multiscale Building Physics (IABP 2024), Lecture Notes in Civil Engineering (Vol. 553). Springer, Singapore. https://doi.org/10.1007/978-981-97-8309-0_10

National Oceanic and Atmospheric Administration (NOAA). (2020). U.S. Climate Normals 1991–2020. National Centers for Environmental Information. https://www.ncei.noaa.gov/products/us-climate-normals

O'Brien, L., Li, L., Herzog, B., Snow, J., & Friess, W. A. (2025). Field monitoring and modeling of the hygrothermal performance of a cross-laminated timber and wood fiber-insulated building located in a cold climate. Sustainability, 17(17), 7879. https://doi.org/10.3390/su17177879

Palani, H., Khaleghi, H., Salehi, P., & Karatas, A. (2023). Assessing hygrothermal performance in building walls engineered for extreme cold climate environments. Sustainability, 15(24), 16597. https://doi.org/10.3390/su152416597

Park, J. H., Kang, Y., Kang, S. T., & Kim, S. (2025). Assessment of hygrothermal performance of ply-lam CLT wall assemblies in a dry-winter humid continental climate region. Building and Environment, 277, 112912. https://doi.org/10.1016/j.buildenv.2025.112912

Picciotto, D. A. B., Nielson, C., & Fiocchi, L. C. (2023). Hygrothermal analysis of double-stud wood walls in non-residential construction: Case study: R.W. Kern Center (Amherst, MA). Journal of Green Building, 18(4), 17–36. https://doi.org/10.3992/jgb.18.4.17

Salonvaara, M., & Desjarlais, A. (2024). Impact of insulation strategies of cross-laminated timber assemblies on energy use, peak demand, and carbon emissions. Buildings, 14(4), 1089. https://doi.org/10.3390/buildings14041089

Salonvaara, M., Gehl, T., Atchley, J., Hun, D., Flechas, G., & Tabares-Velasco, P. C. (2025). Evaluation of the energy, hygrothermal, and thermal capacity performance of cross-laminated timber. The U.S. Department of Energy's Oak Ridge National Laboratory, ORNL/TM-2024/3356. https://doi.org/10.2172/2573622

Wang, L., & Ge, H. (2016). Hygrothermal performance of cross-laminated timber wall assemblies: A stochastic approach. Building and Environment, 97, 11–25. https://doi.org/10.1016/j.buildenv.2015.11.034