# OpenHOUse: A Thermodynamic Living System

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**Abstract**

This paper reports on the design and development of a housing prototype for the Gateway Decathlon international competition. Housing scarcity, global warming, and the need for resilient solutions drove the central approach that defined the design. The developed prototype challenges conventional housing layouts and operational patterns by employing theories of openness in architecture and computational analytics on environmental performance, providing the foundation for a flexible and scalable design suitable for changing conditions. Our analysis demonstrates the potential of open designs to leverage local climates in creating thermally diverse and comfortable conditions while encouraging variability.

## Introduction

Housing occupies a critical space within our contemporary architectural discourse and everyday life. Despite its recognition as an essential human right, in 2023, the U.S. faced a significant housing deficit, with an estimated shortage of around 3.2 million homes[1]. This shortage is further complicated by the building industry being responsible for 37% of global energy-related carbon emissions[2], highlighting a dual challenge: meeting housing demand while advancing environmental goals. To address these issues, sustainable buildings that prioritize low-energy and low-carbon strategies align with global efforts toward carbon neutrality, aiming to reduce the impact of climate change. However, a narrow focus on carbon reduction and energy savings risks compromising essential aspects like thermal resilience and occupant health[3]. While energy efficiency remains a central goal in sustainable design, the industry increasingly acknowledges the importance of safe, healthy, and productive indoor environments.[4]

Technological advancements in the mechanical conditioning of spaces during the 20$^{th}$ century have greatly influenced building design, leading to the widespread adoption of sealed building envelopes to protect occupants' health and safety[5]. At the same time, our modern lifestyle increasingly supports indoor living and controlled thermal zones, promoting the notion that thermal neutrality (lack of thermal exchange) is a synonym for thermal comfort. However, naturally ventilated and semi-outdoor spaces are associated with improved mood and physical and mental health, often leading to greater satisfaction with the thermal environment. The lack of human-centered considerations in building design may risk amplifying health and comfort disparities. Balancing building energy performance with thermal resilience and health is, therefore, essential.

This paper presents the design development of a scalable living system, rooted in environmental analysis and human-centric approaches. This work integrates conceptual, analytical, and practical methodologies stemming from student efforts in a combined design-build studio and elective course for an international housing competition. While intense analytical tools and numerical exercises assist and inform the design, they are primarily used as educational mechanisms to understand the invisible environmental parameters created by architecture that ultimately define how the space is experienced. The architectural typology that promotes air conditioning and the predominantly indoor lifestyle is challenged through design approaches that promote hybrid conditions benefiting from an architecture of openness to the local climate, habitat, and culture.

**Background**

*OpenHOUse Theories and Basis of Design*

OpenHOUse references John Habraken's notion of Open Bouwen (Open Building)[6] and Oskar Hansen's Open Form[7]. Habraken argues for an architecture that distinguishes the "supports" - the permanent communal or collective infrastructure of the building - from the "infill" - the impermanent customizable or adaptable space of the individual. However, more than simply a "core and shell" vs "interior build-out" philosophy, Open Building is about giving agency to the individual occupants to "make" their environment. OpenHOUse builds on this concept, offering an expanded notion of openness as an alternative to the single-family home. In parallel, OpenHOUse draws on Mark DeKay and Gail Brager's idea of "inhabited periphery,"[8] which suggests linking distinct indoor and outdoor conditions by treating the building envelope as a thick occupied zone. Spaces between indoors and outdoors offer dynamic opportunities where occupants can encounter environmental contrasts and transitions of many types. Our approach extends such conditions typically confined to the building envelope into the very core of the structure, reimagining the spatial and thermal dynamics and redefining the conventional boundaries of domestic space with greater connections to the outdoors.

OpenHOUse is also literally open in both plan and section. It challenges the homogenous conditioning of interior space by leveraging thermodynamic forms and effects to condition a house passively throughout portions of the year. The project learns from a range of vernacular precedents, from the "dogtrot" typology of the southeastern US to the wind tower typologies that originated in Persia and can be found throughout portions of Africa and the Middle East. OpenHOUse combines the Venturi effect (dogtrot) with the convection/buoyancy forces that contribute to stack ventilation. The combination of these passive strategies augments indoor and outdoor microclimates, balancing building performance, human comfort, and well-being throughout the year.

The OpenHOUse design is rooted in an architecture of layers and nested spaces. The first layer or space of an OpenHOUse is an "outdoor room" that provides shelter from the elements, primarily, shade in the summer and solar exposure in the winter. The OpenHOUse further integrates an architecture of hybrid zones, spaces somewhere between an unconditioned and conditioned space (Fig. 1). An OpenHOUse has a fully enclosable interior that can be conditioned; however, it focuses primarily on passive ventilation. The large central living space can be completely open, resembling a semi-outdoor condition and thermal environment more than a fully indoor space.

*Thermal comfort integration*

Despite notable advancements in the field, a critical gap persists in integrating thermal comfort modeling with the performance evaluation of housing projects, particularly in climates characterized by pronounced seasonal extremes. Existing research has largely focused on static thermal comfort standards, leaving the potential of adaptive thermal comfort models underexplored. Such models include the ASHRAE Standard 55 (American Society of Heating, Refrigerating, and Air-Conditioning Engineers) and the ISO 7730 (International Organization for Standardization). These standards rely on predictive models such as the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD), based on assumptions about metabolic rates, clothing insulation, and steady-state conditions. While useful for designing controlled environments, these standards may fail to adequately address the dynamic nature of human adaptation to changing or extreme climates, highlighting the limitations of such approaches in certain contexts, such as housing in regions with significant seasonal variability. On the other hand, adaptive models that account for human adaptability to varying thermal conditions remain underutilized in assessing housing designs. As a result, the potential for optimizing comfort while reducing energy consumption through such models has yet to be fully realized, underscoring the need for a more comprehensive approach to housing design in extreme climates.

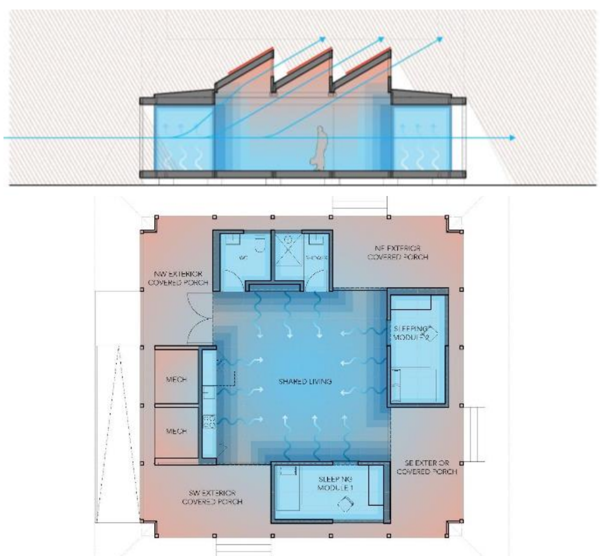



*Fig. 1. Conceptual building diagram of thermal gradients*

Moreover, the role of user behavior in influencing energy performance represents another underexamined dimension of thermal comfort in housing. Studies[9,10] highlight the significant impact of occupant habits on energy consumption, revealing the interplay between design, technology, and human interaction. Despite this, housing performance assessments seldom integrate predictive models of user behavior with passive design strategies. Bridging this gap requires a holistic methodology that combines adaptive thermal comfort modeling with an understanding of occupant dynamics, enabling housing solutions development that is energy-efficient and responsive to human needs.

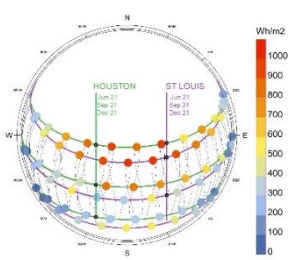
**Methods**

OpenHouse challenges traditional performance metrics, complementing standard energy and carbon indices with early-design, single-aspect evaluations that define architecture and human experience and enhance health and well-being while promoting resilience. It adopts an experimental approach by evaluating performance in two climates, one where the competition will take place (St Louis, MO, IECC climate zone 4a, Lat: 38°37′38″N) and one that will be the building's permanent location (Houston, TX, IECC climate zone 2a, Lat: 29°45′46″N). Our methodologies include climate analysis, solar envelope and shadow studies, and computational simulations. Early design simulation models involved daylighting, computational fluid dynamics (CFD), and thermal comfort modeling before the whole building multi-zonal energy assessment. This approach is aimed at comparative analysis that does not target specific numerical goals and emphasizes the more qualitative aspects of the design while using indices that promote adaptation.

*Climate analysis*

The two climates were compared using weatherspark[11] to facilitate prioritizing building strategies for a responsive building (Table 1). Houston is hotter year-round, with increased humidity, resulting in perceived summer temperatures much higher than recorded. St. Louis winters are colder with higher chances of freezing. The two locations share wind patterns and intensity annually and seasonally. The average daily incident shortwave solar energy experiences significant seasonal variation during the year in both cities. Shortwave radiation includes visible light and ultraviolet radiation. The brightest part of the year is during the warmer months, and the darkest period is during the colder months.

*Table 1: Tabulated climate data for St. Louis and Houston*

| | St. Louis | Houston |
|---|---|---|
| Summers<br>Winters | Hot, muggy<br>Very cold, snowy | Hot and oppressive<br>Cool |
| Avg temperatures | 25°F - 89°F, rarely <9°F, > 97°F | 47°F - 95°F, rarely <9°F, > 97°F |
| Predominant sky | Partly cloudy | Partly cloudy |
| Clearer skies period | 4.5 months (Jun-Oct) | 2.7 months (Sep-Dec) |
| Predominant wind directions | S/SSE (Feb-Dec) | S, SSE (Feb-Sep, Oct-Dec) |
| Windier period | Oct-May | Oct-Jun |
| Avg wind speed | 7.7 mph | 7.8 mph |
| Windiest month | March, avg wind speed 9.3 mph | March, avg wind speed 9.8 mph |
| Calmest month | August: avg wind speed 5.8 mph | August: avg wind speed 6.3 mph |
| Calmer part of the year | 4.8 months (May to Oct) | 4.3 months (Jun to Oct) |
| Avg daily incident shortwave solar | summer:5.9kWh/$m^2$<br>winter:3.0kWh/$m^2$ | summer:5.9kWh/$m^2$<br>winter:3.7kWh/$m^2$ |
| Sun-path Diagrams colored per global horizontal irradiance during key days |  | |

*Daylight modeling*

The baseline building was modeled with wall thicknesses and all neighboring obstructions without building shading. The analysis grid (spacing: 0.5 ft, offset from floor: 2.5 ft) was placed in all occupied spaces. Although not a typical practice, the bathrooms are included, considering natural light in this space benefits occupants' well-being and resilience.

Annual metrics - Useful Daylight Illuminance (UDI), Spatial Daylight Autonomy (sDA), and Annual Sunlight Exposure (ASE) - were used to evaluate strategies and compare the two climates. For calculating UDI in the main spaces (living, kitchen, bedrooms), the target illuminance was 300 lux, the supplemental illuminance 100 lux, and the excessive illuminance 3000 lux. In the bathrooms, the target illuminance was 100 lux, the supplemental illuminance was 50 lux, and the excessive illuminance remained at 3000 lux. In all spaces, the sDA time was 50%, and the occupancy was assumed between 8 am and 6 pm, accounting for daylight savings. All interior surfaces were modeled as wooden with visual light reflectance values at 36.6% for the exposed columns, ceiling, and walls and 35.1% for the floors. All glazing surfaces had a 68% visible light transmittance.

The analysis was performed using Radiance®[12] in ClimateStudio® v2.0. Five scenarios were tested cumulatively, starting with the early design baseline. The scenarios were developed based on observations on the baseline and targeted the highest autonomy (maxing UDI and sDA) and the lowest glare potential (minimizing ASE). The design gradually progressed from the baseline to iteration #1, adding top-lighting with nine vertical, north-facing skylight configurations above the central space; iteration #2, adding windows in the bathrooms that were initially considered non-daylit; iteration #3, reducing the size of the bedroom windows, and iteration #4, incorporating design details, such as mullions, updated thickness at roof extension, and structural obstructions.

*Air movement*

Eddy3D®[13] was used for computational fluid dynamics (CFD) simulations. Eddy3D plugin uses blueCFD®[14], a software package of a high-quality cross-compiled build version of OpenFOAM®[15]. Three scenarios were tested to evaluate the effectiveness of the design in the central space: 1) Single-sided ventilation with one fully open window facing the wind direction, 2) Cross-ventilation with two facing fully open windows parallel to the wind direction, and 3) Stack-ventilation with one window open facing the wind direction and three skylight windows open to match the inlet and outlet area. The best-performing scenario (3) was used to test eight wind directions (S-SE-E-NE-N-NW-W-SW) and evaluate favorable inlet/outlet modes. For example, the SE window (inlet) and the skylights (outlet) were opened to test the east wind.

In the early design phases, a 4 m/s wind speed coming from the cooling-season predominant SSE direction was used. The boundary geometry included the extended roof, no additional shading or other obstructions, and assumed a flat terrain. During the early phases, the simulation domain consisted of the building geometry (W: 14m, L: 14m, H: 5m) with a projected facade area of 89 $m^2$. With a 5m block size, the box domain (W: 94m, L: 113m, H: 30m) consisted of 18 cells along the width, 22 cells along the length, and 5 cells along the height. For the later cardinal simulations, a cylindrical domain was used with a projected area of 88.9m and the smallest cell size at the center at 5m. In both cases, with a desired cell size of 0.1m, the mesh accuracy level for the building and the features (corners) meshes was 6. The level of accuracy for the building boundary box and the ground was optimized at 1. The simulation meshing mode used block snapping and no layers. 2250 iterations were simulated at each run with the realizableKE turbulence model and optimized relaxation factors.

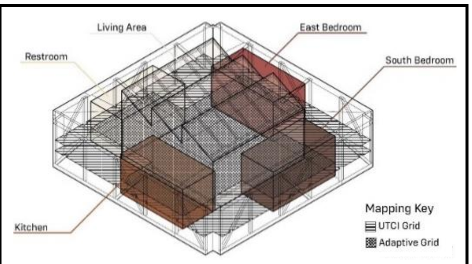
*Thermal comfort*

The project's spaces were evaluated using different thermal comfort models depending on their ventilation mode and use. Although all interior occupied spaces have access to mechanical conditioning, the evaluation of the space assumed the moments during the year when natural ventilation is possible and desired; that is a typical mid-season day. Therefore, the adaptive thermal comfort model[16] was used in interior spaces when a heating or cooling system is not operational and occupants can open windows for natural ventilation. For the outdoor protected patio spaces, the UTCI comfort model is used[17]. UTCI is an international standard for outdoor temperature sensation (aka "feels-like" temperature) and is strictly used for the outdoors. While UTCI is designed to be valid in all climates and seasons, it assumes that human subjects naturally adapt their clothing to the outdoor temperature. The comfort simulations were performed using LadybugTools® v1.8.0 plugin.

The UTCI and adaptive comfort calculations use EnergyPlus®[18] to obtain surface temperature, indoor air temperature, and indoor humidity values. Outdoor air temperatures and relative humidity values, were taken directly from the EPW file. Airspeed was also taken from the EPW file for UTCI but was assumed to be 0.5 m/s for the adaptive comfort calculations. The energy properties of the model geometry were what determined the outcome of the simulation. Longwave radiant temperatures were obtained by computing spherical view factors from each sensor to the zone surfaces of the model using Radiance. These view factors were then multiplied by the surface temperatures output by EnergyPlus to yield longwave mean radiant temperature (MRT) at each sensor. All indoor shades were assumed to be at the room-average MRT. For outdoor sensors, each sensor's sky view was multiplied by the EPW sky temperature to account for longwave radiant exchange with the sky. All outdoor context shades and the ground were assumed to be at the EPW air temperature. A Radiance-based enhanced 2-phase method was used for all shortwave MRT calculations, which precisely represents direct sun by tracing a ray from each sensor to the solar position.

The simulation workflow began with the OpenHOUse baseline model, without any shading. All bounding parameters, such as building materials, construction parameters, EPW files, and simulation periods are listed in Table 2. Adaptive and UTCI indices were used to compare different shading conditions against the baseline model iteratively. First, the effectiveness of the extended roof above the patios and at the perimeter of the building were assessed. In addition to that, two perforated screening systems were positioned vertically at the patios and assessed separately. The screenings were characterized by distinct perforation patterns that follow the solar path per orientation and modulate solar heat gain, shading, and ventilation. Their effect on thermal comfort were tested and compared against the baseline model. The outputs consist of UTCI temperatures during a typical summer day, when extra shading may be needed to make outdoor spaces occupiable, and Adaptive Thermal Comfort maps in the interior during a typical mid-season day when it is more likely to utilize natural ventilation.

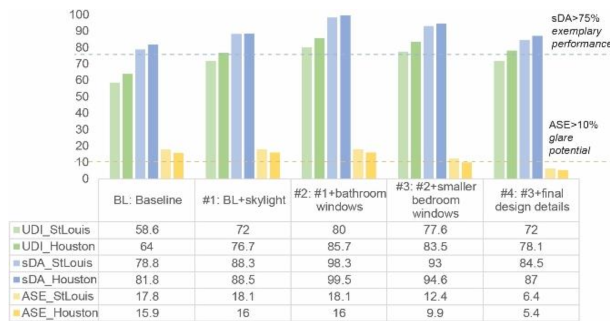
*Table 2: Boundary input parameters for comfort simulations*

| | |
|---|---|
| Baseline geometry diagram |  |
| Location | St. Louis: 38°34'15"N, 90°09'22"W, Cfa<br>Houston: 29°38'44"N, 95°16'44"W, Cfa |
| Climate file | USA_IL_Cahokia-St.Louis.Downtown.AP.725314_US.Normals.2006-2020<br>USA_TX_Houston-William.P.Hobby.AP.722435_TMY3 |
| North offset | St. Louis: 25° CCW from N<br>Houston: 19°CCW from N |
| Constru-ctions | Houston (IECC 2a): External wall R11, typical wood joist attic floor-R38, typical insulated -R4 slab floor, windows: U-0.325, SHGC 0.22<br>St. Louis (IECC 4a): External wall-R15, wood joist attic floor-R48, typical insulated slab floor-R5, windows: U-0.325, SHGC 0.22 |
| Analysis grid | Spatial Resolution: 0.5 m; Total grid points: 485; Vertical offset from floor: 90 cm |
| Conditio-ning | All interior spaces are modeled as naturally ventilated with 50% operable area on windows |
| Simulation Days | Adaptive: 9/21 (St. Louis), 9/25 (Houston)<br>UTCI: typical summer day: 7/21 |
| Simulation Period | Adaptive: 24 hours, 00:00-23:00<br>UTCI: 8 hours, 8:00-18:00 |

**Results**

*Daylight*

Close adherence to climate-relevant rules of thumb and design experience resulted in a well-performing baseline. Differences between the two climates are negligible, with daylighting slightly more favorable for Houston, achieving higher autonomy and lower glare potential. From the baseline model to iteration #4, UDI improved on average 31%, sDA 17%, and ASE 34% (Fig. 2).




| | BL: Baseline | #1: BL+skylight | #2: #1+bathroom windows | #3: #2+smaller bedroom windows | #4: #3+final design details |
|---|---|---|---|---|---|
| UDI_StLouis | 58.6 | 72 | 80 | 77.6 | 72 |
| UDI_Houston | 64 | 76.7 | 85.7 | 83.5 | 78.1 |
| sDA_StLouis | 78.8 | 88.3 | 98.3 | 93 | 84.5 |
| sDA_Houston | 81.8 | 88.5 | 99.5 | 94.6 | 87 |
| ASE_StLouis | 17.8 | 18.1 | 18.1 | 12.4 | 6.4 |
| ASE_Houston | 15.9 | 16 | 16 | 9.9 | 5.4 |

*Fig. 2: Daylight simulation results evaluating UDI, sDA, and ASE for the five tested scenarios in Houston and St Louis.*

*Air movement*

The early-phase CFD air movement analysis created a comparative evaluation between the tested scenarios (Fig. 3 top). The single-sided ventilation mode generated air speeds <1 m/s inside the building, more suitable during winter and mid-season months. This mode offers two wind-protected patios at the leeward side, while the windward patios reach speeds 1.1 to 2.5 m/s. The cross-ventilation and the stack effect scenarios are comparable in the interior, reaching speeds up to 1.5-1.8 m/s. In both cases, the one-half of the building that aligns with the inlet window gets most of the high-speed air. Adjusting the opening windows diverts this imbalance to the other side, but it is unlikely to achieve high-speed air in the entire space. Cross ventilation transfers the exhaust air to the leeward side resulting in three high-air-movement patios, while the stack effect scenario resembles the single-sided effect in the outdoors.

The cardinal direction wind tests highlight the effectiveness of the design for different wind directions (Fig. 3 bottom). The window positioning and the rotation of the building offer the ability to control the inlet window to capture the wind direction, providing flexibility to the space and underlining the design's acuity. Almost all tested scenarios yield similar results with the E, SE, S, and W directions yielding the highest air movement, while also covering the majority of the space. All cases result in at least one wind-protected patio.

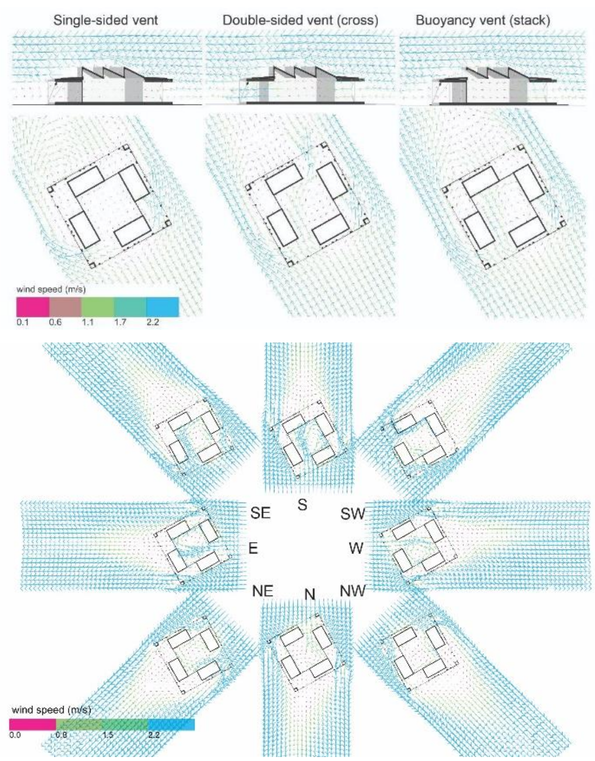



*Fig. 3: CFD results for the three tested scenarios (top), and for the stack effect on eight cardinal wind directions (bottom).*

*Thermal comfort*

Hourly comfort mapping provides a more accurate representation of actual temperatures. St. Louis and Houston differ in key temperature ranges due to distinct hourly max and min values, but their hourly temperature patterns remain comparable due to similar local climate characteristics.

Initially, hourly operative temperatures (OT) in the interior spaces during a typical mid-season day and UTCI on the patios during a typical summer day were captured (Fig. 4). The tested shading options have a profound effect on lowering higher temperatures, while lower-range temperatures are not affected negatively. The biggest impact is noted by the extended roof justifying its existence benefiting both the interior and the exterior. The perforated shading designs are comparable with shading 1 performing slightly better. When the interior OT reaches above 28°C, the capacity of all shading to lower the temperatures decreases. The on-grid temporal OTs achieved with shading from the roof and shading 1 were further analyzed as maps of the degree Celsius from the adaptive comfort neutral temperature. The min, max, and average grid values for every simulated instance were subtracted from the min, max, and average values of the baseline grid values returning the Adapt-$\Delta T_{min}$, Adapt-$\Delta T_{max}$, and Adapt-$\Delta T_{avg}$ values. Similarly, the minimum, maximum, and average grid UTCI temperatures were calculated for every simulated instance and subtracted from the no-shading baseline scenario UTCI temperatures returning the UTCI-$\Delta T_{min}$, UTCI-$\Delta T_{max}$, and UTCI-$\Delta T_{avg}$ values. All ΔT values were plotted against outdoor dry bulb temperatures to evaluate the shading effectiveness (Fig. 5).

In both cases, a positive correlation is noted; the higher the outdoor temperatures the higher the drop in perceived temperature. In the adaptive model, the linear correlation is much tighter with $R^2$ between 0.47 and 0.60 for the three categories. In addition, the temperature drops are more pronounced among the max temperatures, followed by the average and the lowest. Finally, when outdoor temperatures exceed 28°C, the shading effectiveness starts decreasing. In the UTCI model, there is no substantial linear correlation for the tested temperatures, and the temperature drops are more pronounced among the average temperatures, followed by the max, and the min.

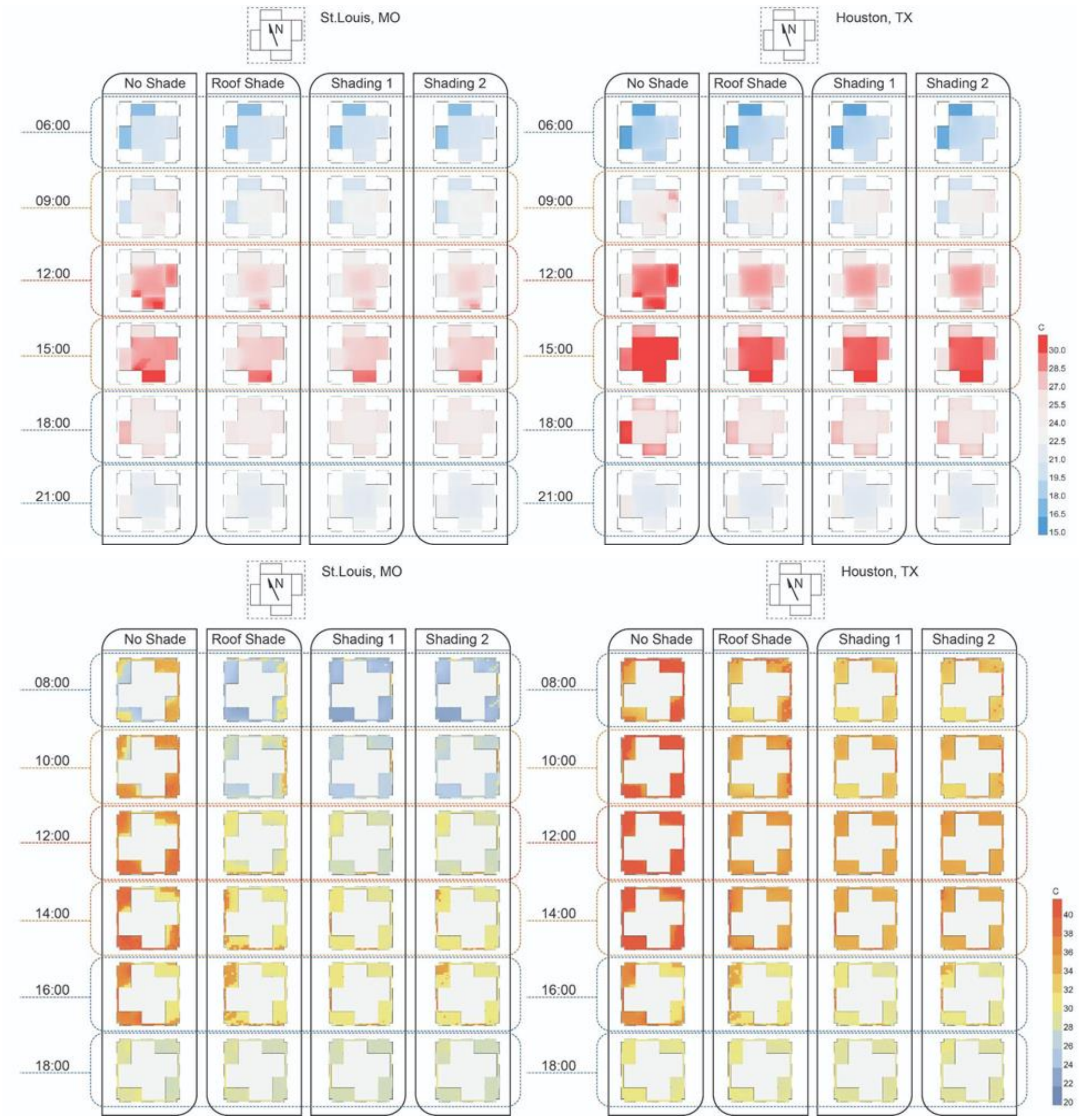



*Fig. 4: Operative temperature maps during a typical mid-season day (top) and UTCI temperature maps (bottom) during a typical summer day in St. Louis and Houston for the four tested scenarios*

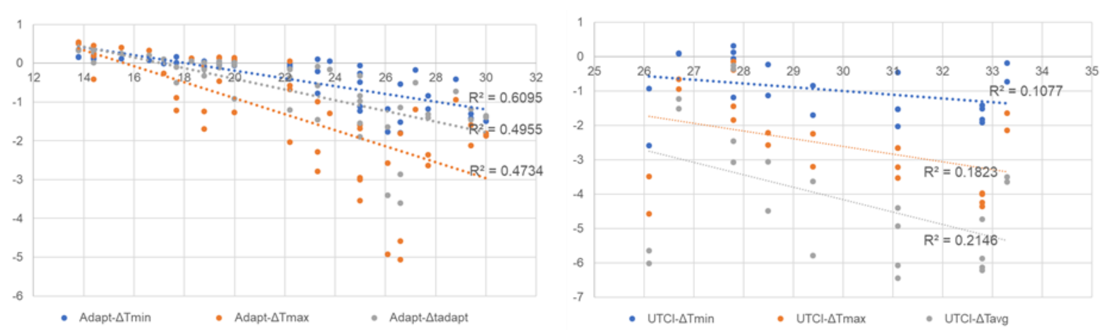



*Fig. 5: Relationship between outdoor dry bulb temperatures (x-axis) and operative temperatures degree Celsius difference (left), or UTCI temperatures (right), computed as ΔT values of the shaded model against the baseline non-shaded one.*

**Discussion**

Early performance analysis assisted with decision-making during the design development of the OpenHOUse. Each single-aspect simulation model provided valuable input directing design decisions, such as orientation, window sizing, envelope composition, and operational guidelines. By analyzing the building's permeability, shading, and ventilation modes, the project finds productive overlaps between adaptive thermal comfort theories and the need for adaptable and inclusive living arrangements.

The daylight and ventilation models underlined the effect of the skylight, especially for the St. Louis skies. Daylight autonomy was further improved by re-sizing and adding windows, with sDA remaining >75%, and ASE <10% in both climates. Such exemplary performance was achieved without movable or high-maintenance means, but solely by the building's self-shading, orientation, and window configurations.

The CFD studies further reinforced the benefit of the skylight underlining its capacity to work with all four sliding-door openings. The building's orientation and flexible windows allow for different ventilation modes during various times of the year. Well-shaded, vertically unobstructed, large openings facilitate air movement individually or in pairs for cross ventilation.

Thermal comfort studies indoors and at the patios highlighted the benefit of the roof extension. Its benefit on indoor comfort is pivotal during mid-season. When it is combined with natural ventilation OTs can drop substantially, considerably extending the period during which mechanical conditioning is not needed. In both climates, mechanical conditioning can be limited to one or two hours per day during mid-season when the outdoor temperatures exceed 28ºC. On outdoor comfort, the roof's benefit is highlighted especially during summer, when spending time outdoors -particularly in Houston- can become challenging. Extreme (>46ºC) and strong (38-46ºC) heat stress can be reduced substantially, while the additional vertical perforated panels can even further reduce perceived temperatures eliminating heat stress to only a few instances of moderate (26-32ºC) heat stress.

**Conclusion**

This project demonstrates the potential of OpenHOUse as a scalable and adaptable housing prototype, developed to address critical challenges such as housing scarcity, environmental sustainability, and thermal resilience. By integrating architectural theories of openness with computational tools for environmental performance analysis, the project reimagines the boundaries of domestic spaces. The design challenges conventional notions of thermal neutrality and embraces the variability of local climates to create thermally dynamic and comfortable living conditions. The analysis highlights the advantages of passive strategies, such as ventilation and shading, while maintaining adaptability to diverse climates. From daylight optimization to enhanced air movement and thermal comfort modeling, OpenHOUse demonstrates the capacity to balance energy efficiency with human-centered considerations, contributing to more resilient and sustainable housing. The use of computational simulations underscores the importance of integrating adaptive thermal comfort models, addressing seasonal extremes and dynamic occupant behavior to inform design decisions.

Through its open-plan design, modularity, and focus on environmental responsiveness, OpenHOUse presents a compelling framework for addressing the challenges of contemporary housing. By drawing from vernacular precedents and integrating computational performance analysis, the project aligns with global sustainability goals while prioritizing occupant health and well-being. On a broader level, this work contributes to ongoing architectural discourse by advocating for a paradigm shift that transcends static, sealed environments in favor of hybrid conditions that reconnect architecture with its surrounding climate and culture. As the building industry continues to grapple with the dual crises of housing scarcity and climate change, OpenHOUse serves as a model that is contextually responsive. This study affirms the importance of merging analytical precision with human experience, setting a foundation for future explorations in adaptable, sustainable, and inclusive residential design.

**Acknowledgements**

The authors thank all research assistants and undergraduate and graduate students who worked on the OpenHOUse project in Fall 2024. In particular, they thank Diego Contreras Rios and Cameron Klassen for their contributions to the studies and image production.

**Notes**

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