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AI-Driven Parametric Evaluation of Thermal Comfort in Vernacular Heritage: A courtyard-centric study of Unnati School, Ahmedabad, India

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ABSTRACT

This research investigates how courtyards of traditional Ahmedabad pol houses that have been adaptively reused as institutional spaces regulate microclimates. Focusing on Unnati School, the study addresses how high occupancy (213 users) and modern materials such as steel roofing impact heritage cooling performance. The methodology bridges vernacular wisdom with computational synthesis, employing AI-driven voxel simulations via the Infrared.city platform to calculate the Universal Thermal Climate Index (UTCI). To ensure technical accuracy, digital simulations are verified against on site thermometer readings. The study contributes to heritage and climate-responsive design research by proposing a rapid, scalable framework for evaluating thermal comfort in adaptively reused heritage buildings and by demonstrating the applicability of AI-driven environmental simulations as an alternative to more resource-intensive Computational Fluid Dynamics (CFD) approaches. Findings identify thermal tipping points where modern interventions diminish the cooling benefits of traditional courtyard systems. By comparing AI-based and conventional thermal assessment methods, the research provides new evidence on the reliability of emerging digital tools for heritage performance evaluation. The study further demonstrates that the courtyard stack effect functions as a measurable and effective passive cooling mechanism, offering a data-driven basis for integrating vernacular design principles into contemporary heritage conservation and climate adaptation strategies.

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1. Introduction

The historic walled city of Ahmedabad is the first UNESCO World Heritage City and it is an unprecedented urban laboratory for the study of climate-responsive vernacular architecture. The *Pol* system is an integral part of the city's architectural identity that forms a dense network of residential clusters, which have grown organically over centuries of occupation, with shared masonry walls and intricate timber-frame structures, which are adaptable to the region's extremely hot-dry climate (Heritage, 2017).

Beyond their architectural significance, the *Pols* of Ahmedabad represent a sophisticated traditional knowledge system that integrates social organization, environmental adaptation, and resource-efficient urban design. (Neeta Lambe, 2016) Developed over generations through collective experience, these settlements embody locally evolved responses to the region's climatic conditions, cultural practices, and patterns of community living. Narrow streets, compact urban form, shaded public spaces, internal courtyards, carved wooden facades, and interconnected housing clusters work together to moderate microclimatic conditions by reducing solar exposure, enhancing ventilation, and facilitating thermal regulation. (Desai, 2026)

The courtyard, in particular, functions as a critical environmental device that supports daylighting, air circulation, and passive cooling through stack-effect-driven ventilation. (Neeta Rajesh Lambe, 2017) These spatial and architectural strategies demonstrate how traditional communities developed climate-responsive solutions long before the advent of mechanical cooling systems, making the *Pols* an important repository of vernacular knowledge for contemporary discussions on sustainable urbanism and climate adaptation.

As many *Pol* houses undergo functional transformation from residential use to institutional, commercial, and community-serving functions, understanding the performance of these traditional environmental systems under new occupancy patterns becomes increasingly important. (Rajan Rawal, 2017) Such adaptive reuse offers an opportunity not only to conserve built heritage but also to retain and reinterpret the climatic intelligence embedded within these traditional knowledge systems and climate-responsive neighbourhoods. (Gangwar, 2020)

The relevance of these passive design strategies has become increasingly significant in the context of rising urban temperatures and climate change. Studies on Ahmedabad's traditional urban morphology have demonstrated that compact street networks, shaded public realms, and courtyard-based housing contribute to improved thermal comfort and lower exposure to extreme heat, thereby reducing dependence on mechanical cooling. (Mahadevia Darshini., 2020)

Furthermore, evidence from contemporary housing in Ahmedabad indicates that occupants often experience thermal discomfort and increased energy consumption in buildings that lack climate-responsive design features. As the frequency and intensity of heatwave events continue to increase in hot-dry regions such as Ahmedabad, traditional building knowledge embedded within the Pols offers valuable insights for developing resilient, energy-efficient, and climate-adaptive urban environments. (Garima Kamra, 2019) (Dutta, 2022).

1.1 Background and Context

In this context, the traditional Pol house can be regarded as a refined environmental machine by employing high thermal mass and courtyard designs to create microclimates in a region with summer heat often reaching over 45°C (López Cabeza, 2022). In modern times however, the pressures of urbanization and changing functional needs of old buildings have resulted in a dramatic increase in cases of buildings being adapted for new uses, such as the conversion of houses to be used for schools. This change creates a large thermal problem which may conflict with the original passive cooling systems of the vernacular form.

The effectiveness of the courtyard to address the impact of the modern demands on thermal performance in the indoor microclimate is evaluated in this study. The research in this category uses AI-based surrogate modelling to simulate thermal comfort patterns, and assesses the accuracy of the digital prediction with empirical measurements taken in the field and historical performance data (Chaillou, 2022). The study validates the pattern recognition algorithms used in the Infrared.city's platform by comparing the Universal Thermal Comfort Index (UTCI) (Błażejczyk et al., 2013) data generated in the platform with true values from thermometers in complex heritage environments. All these aim to legitimise the stack effect as a science-informed approach to preserve heritage in a changing climate.

1.2 Thermal Behaviour of Courtyard Houses: Evidence from Ahmedabad's *Pol* Architecture

Understanding the thermal behaviour of traditional courtyard houses is essential for evaluating the performance of adaptively reused heritage buildings. Courtyards are a significant part of the *Pol* houses of Ahmedabad considering the priority of thermal comfort as the city falls in the hot and dry climate zone.

A study conducted in *Moti Hamam ni Pol* (neighbourhood in a walled city of Ahmedabad), Ahmedabad, investigated three residential *Pol* houses through field measurements and CFD simulations to assess the influence of courtyards on indoor thermal comfort (Mihir, 2012). The findings established the courtyard as a key passive cooling component, providing an important reference for assessing how such systems perform when subjected to contemporary interventions and altered occupancy patterns.

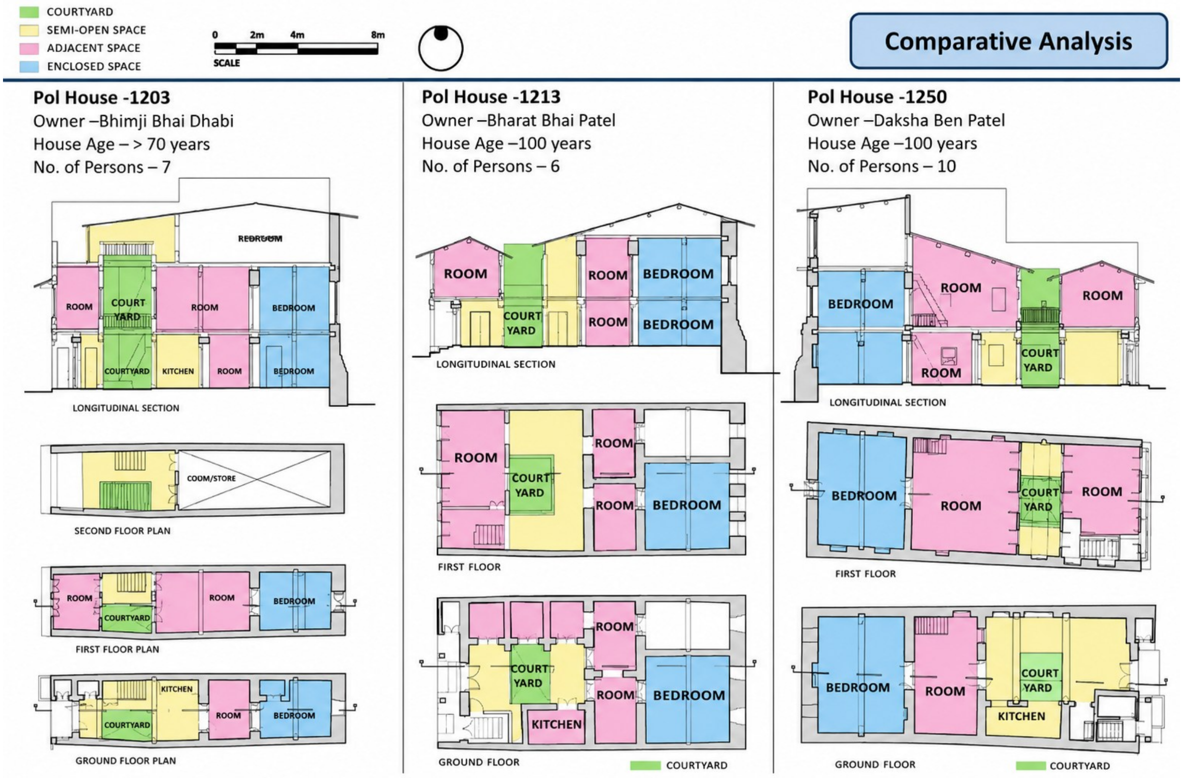


Figure 1 - Comparative Analysis between the three houses. Source: (Mihir, 2012)

The analysis reveals that courtyards function as a "thermal engine" by utilizing the stack effect to draw in cool air and expel heat, alongside the thermal lag of thick masonry walls that radiate heat away at night. Quantitative results demonstrate that houses with courtyards maintain indoor temperatures 2°C to 4°C lower than identical structures without them. Specifically, ground floor rooms adjacent to the courtyard remained the most stable, staying between 31°C and 34°C even during outdoor temperature peaks.

The findings establish the courtyard as a critical climatic moderator within the traditional *Pol* house, where its interaction with thermal mass, building geometry, and ventilation pathways creates a resilient passive cooling system. These observations provide an important benchmark for the present study, which investigates whether such climatic performance can be retained when heritage courtyard houses undergo adaptive reuse and are subjected to altered occupancy patterns and contemporary material interventions.

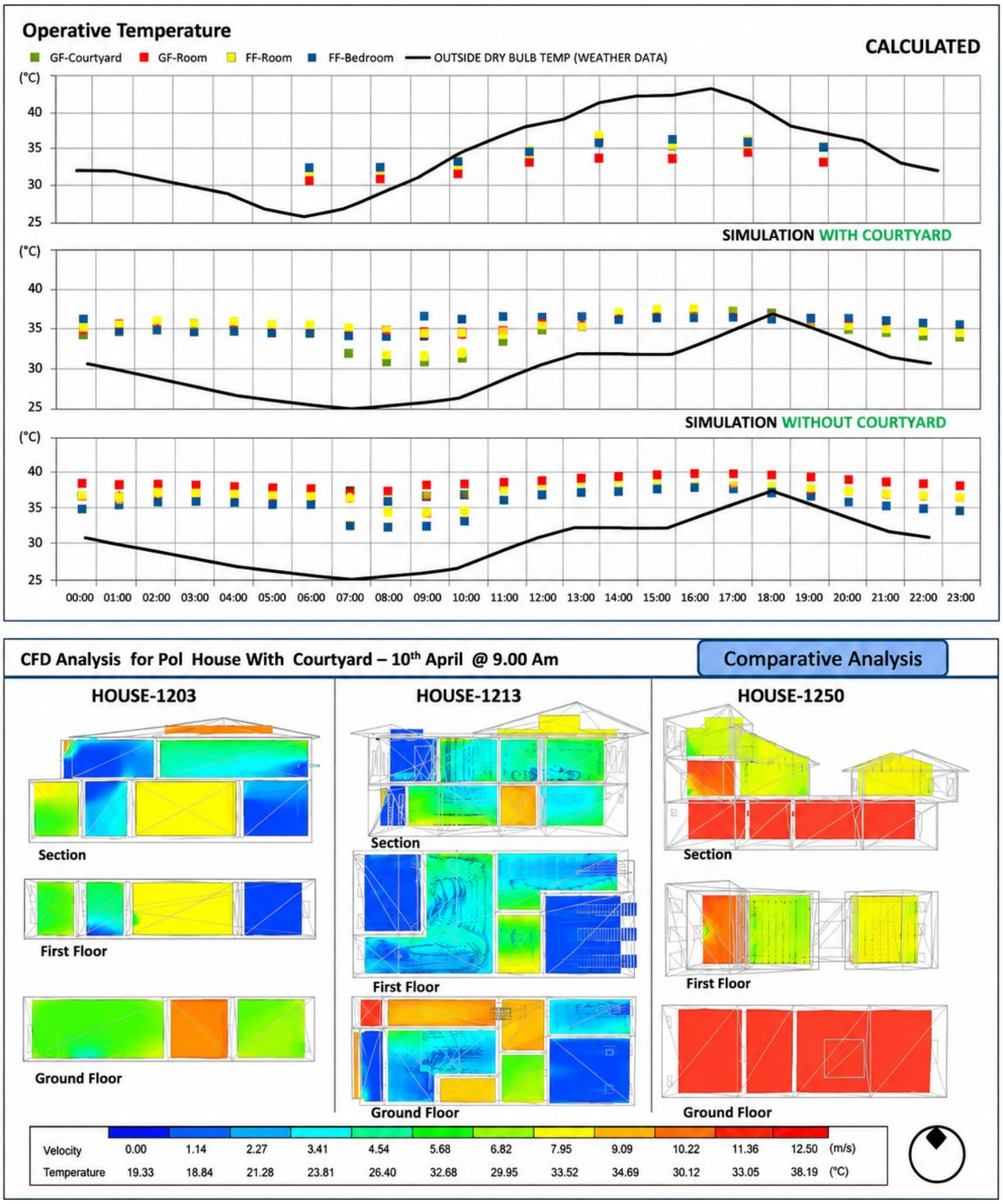


Figure 2 - *Impact of presence of courtyard on thermal characteristics of vernacular residential building: An exploration in hot - dry vernacular context of Ahmedabad.*

2. Research Gap and Objectives

Can AI-driven thermal simulation reliably assess the thermal performance of adaptively reused heritage courtyard buildings, and what does it reveal about the impact of adaptive reuse on thermal comfort?

3. Scope

This research brings together three complementary streams of inquiry - vernacular architectural wisdom, parametric environmental analysis, and AI-driven thermal evaluation. The study employs a parametric assessment of a heritage courtyard building to examine the applicability and reliability of AI-based thermal comfort simulations. Specifically, the research focuses on an adaptively reused traditional *Pol* house, now functioning as Unnati School in Ahmedabad, to evaluate how changes in occupancy patterns and material interventions influence thermal comfort when compared to the building's original residential use.

Beyond its climatic performance, Unnati School represents a broader phenomenon of adaptive reuse within Ahmedabad's historic walled city, a UNESCO World Heritage City. Many traditional *Po*l houses were originally designed to accommodate large joint families and have evolved incrementally over time through the addition of floors, rooms, and other architectural elements. As demographic and ownership patterns change, these buildings present significant opportunities for adaptive reuse as schools, pre-schools, day-care centres, and other community-serving functions. Such transformations can strengthen neighbourhood-level access to educational and social infrastructure while simultaneously supporting heritage conservation. Given that many of these properties are privately owned or managed by trusts, understanding their environmental performance under new patterns of use is critical for informing future adaptive reuse strategies and policy decisions especially when they are to be occupied by the most children or toddlers who are most vulnerable to Heat. (Adora Shortridge, 2022)

4. Limitation of the study

The study is restricted to thermal comfort analysis; other comfort factors like acoustics, etc are not addressed. The research doesn't include full scale physical testing or post occupancy evaluations. As the tool used here in this study, this AI tool is a voxel-based urban climate simulation platform that employs machine learning surrogate models trained on a large dataset of Computational Fluid Dynamics (CFD) and radiation simulations. Rather than directly solving the governing equations of fluid flow and heat transfer for each simulation, the platform predicts thermal conditions using pre-trained models, thereby significantly reducing computational requirements. Inputs include building geometry, land cover, vegetation, meteorological conditions, and solar exposure, while outputs include surface temperature and Universal Thermal Climate Index (UTCI) predictions.
This resulted in some divergence between digital predictions and observed conditions, particularly in capturing the localized 4°C vertical temperature variation associated with internal structural modifications. Additionally, the empirical measurements were collected using handheld instruments during active school hours over a defined monitoring period. While this approach captured peak occupancy conditions of approximately 213 users, it may not fully represent thermal variations across the complete annual climatic cycle.

5. Materials and Methods

The thermal resilience of Ahmedabad's traditional *Pol* houses can be attributed to a combination of architectural strategies that collectively regulate indoor microclimates and enhance occupant comfort under extreme climatic conditions. Central to this performance is the integration of passive cooling mechanisms, including natural ventilation, efficient building envelopes, high thermal mass construction, and the use of internal courtyards.
One of the most significant mechanisms is the stack effect, whereby the courtyard functions as a vertical ventilation shaft. As warm air within the building rises and escapes through the open-to-sky courtyard, cooler air is drawn into the lower levels from the narrow, shaded streets characteristic of the *Pol* settlement pattern. This buoyancy-driven airflow promotes continuous ventilation, facilitating the removal of accumulated heat and improving indoor thermal comfort, particularly during periods of high occupancy. (Rajapaksha, 2018).

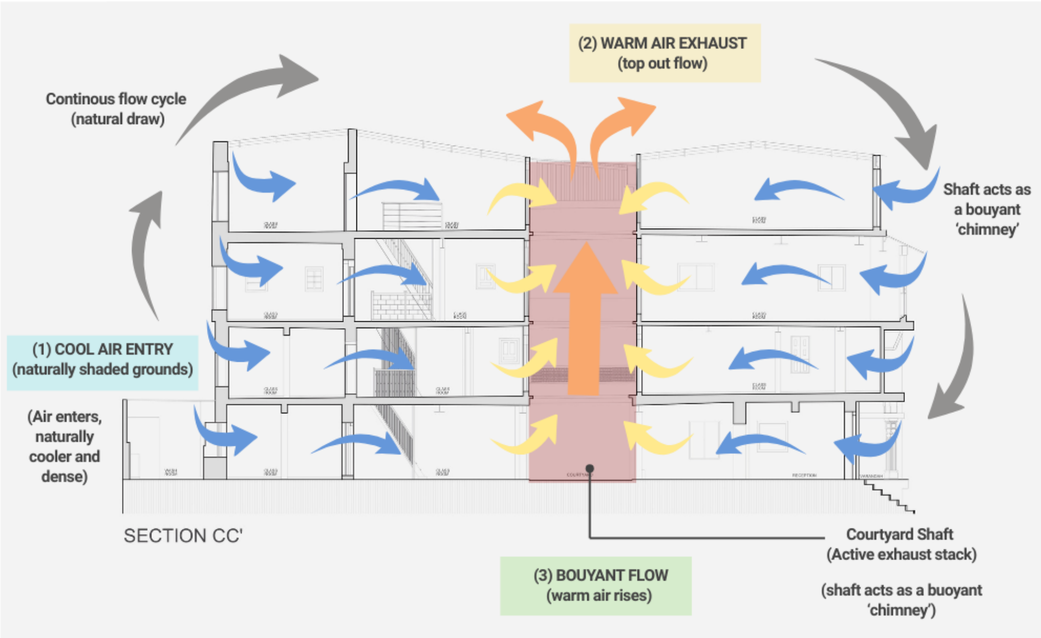


Figure 3 - Diagram showing the working of stack effect.

The compact urban morphology of the *Pol* further contributes to thermoregulation through the principle of shared wall construction. Houses typically share two or more walls with adjacent structures, creating a continuous thermal mass across the settlement. This arrangement minimizes the exposed building surface area and reduces heat gain from solar radiation, thereby moderating temperature fluctuations within individual dwellings and contributing to a more stable neighbourhood microclimate. (Ratti, 2003).

Another important characteristic is the phenomenon of thermal lag, which results from the use of traditional materials such as thick brick masonry and lime plaster. Owing to their high thermal inertia, these materials delay the transfer of heat through the building envelope, ensuring that peak outdoor temperatures do not immediately translate into indoor heat gains (Mihir, 2012). As a result, indoor spaces remain comparatively cooler during the day. During the night, the stored heat is gradually released, while the courtyard assists in dissipating this heat through long-wave radiative cooling to the night sky. Together, these mechanisms demonstrate the sophisticated climatic intelligence embedded within the traditional *Pol* house and highlight its relevance for contemporary discussions on climate-responsive design and heritage conservation.

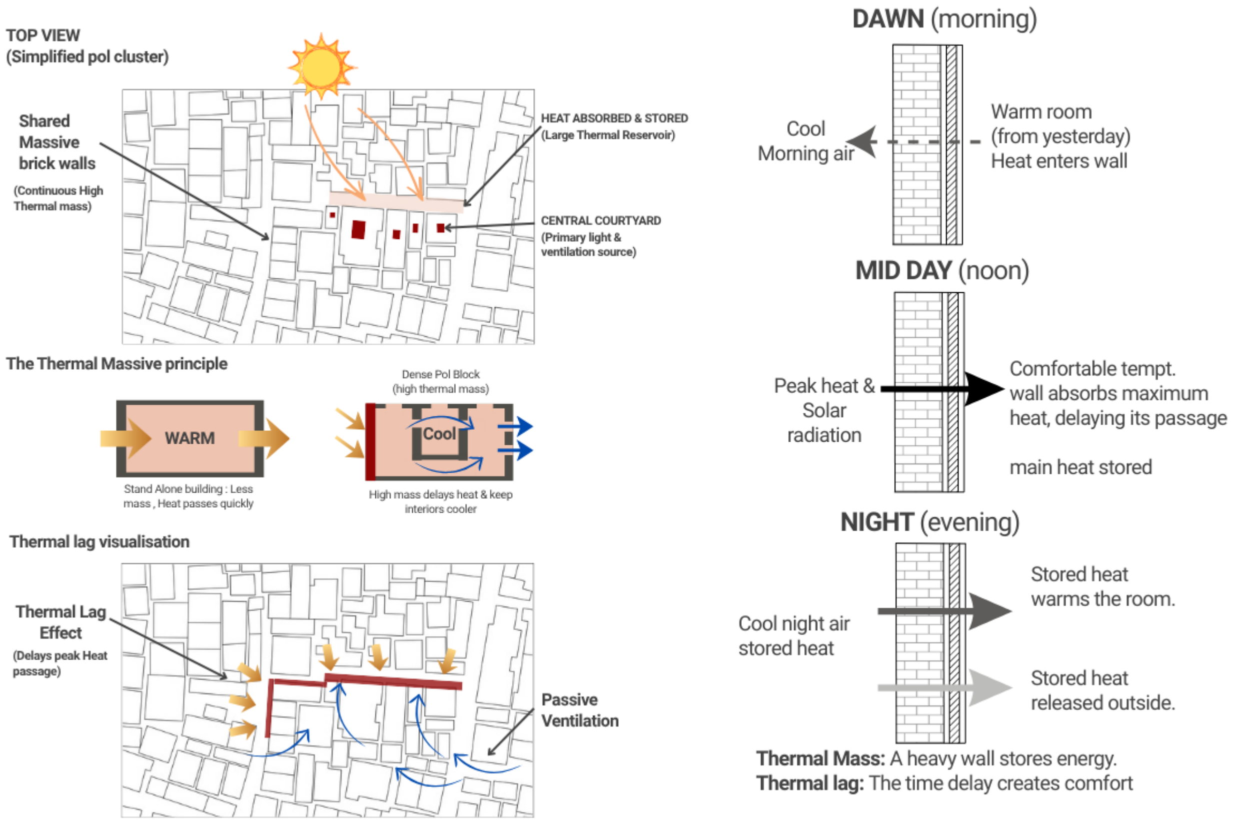


Figure 4 - Diagram showing the working of Shared wall theory and Thermal lag, respectively.

To measure these dynamics, the study utilizes a voxel-based AI surrogate model that maps the Universal Thermal Climate Index (UTCI). UTCI is a human-centric metric measuring physiological reactions to the environment, factoring in mean radiant temperature (MRT) and air speed.

Unlike conventional CFD models that require intensive numerical computations for each simulation, AI-driven surrogate models leverage knowledge derived from thousands of pre-computed high-fidelity simulations to predict thermal comfort and airflow patterns rapidly. This significantly reduces computational time, enabling the efficient evaluation of multiple design scenarios and making the approach particularly valuable for heritage conservation and adaptive reuse projects. (Chaillou, 2022).

6. Methodology

The research follows a hybrid framework that integrates digital simulation with empirical field monitoring as shown in Chart 1 & 2. The initial phase involves the selection of thermal comfort parameters for the internal spaces of the studied built environment, here Unnati School, that are organized around the central courtyard. A 3D model of the school and its immediate urban context in Jethabhai ni *Pol* (A neighbourhood where the school building is located) was developed using Rhino and Grasshopper modeling. This model accounts for the specific geometric porosity of the Pol fabric, pulling in a context radius of up to 1 km to ensure that the "shared wall" effects of the neighborhood are represented in the analysis.

The simulation engine utilizes a voxel-based AI approach to map the UTCI across the site. UTCI is a modern, human-centric metric that measures how the human body physiologically reacts to the entire environment, including mean radiant temperature (MRT) and air speed.

To ensure the simulation aligns with the physical reality of the adaptively reused school, the digital model was manually re-edited to accurately reflect existing courtyard voids and modern structural interventions like the steel roofing. (Rajaa Gunasekaran, 2025)

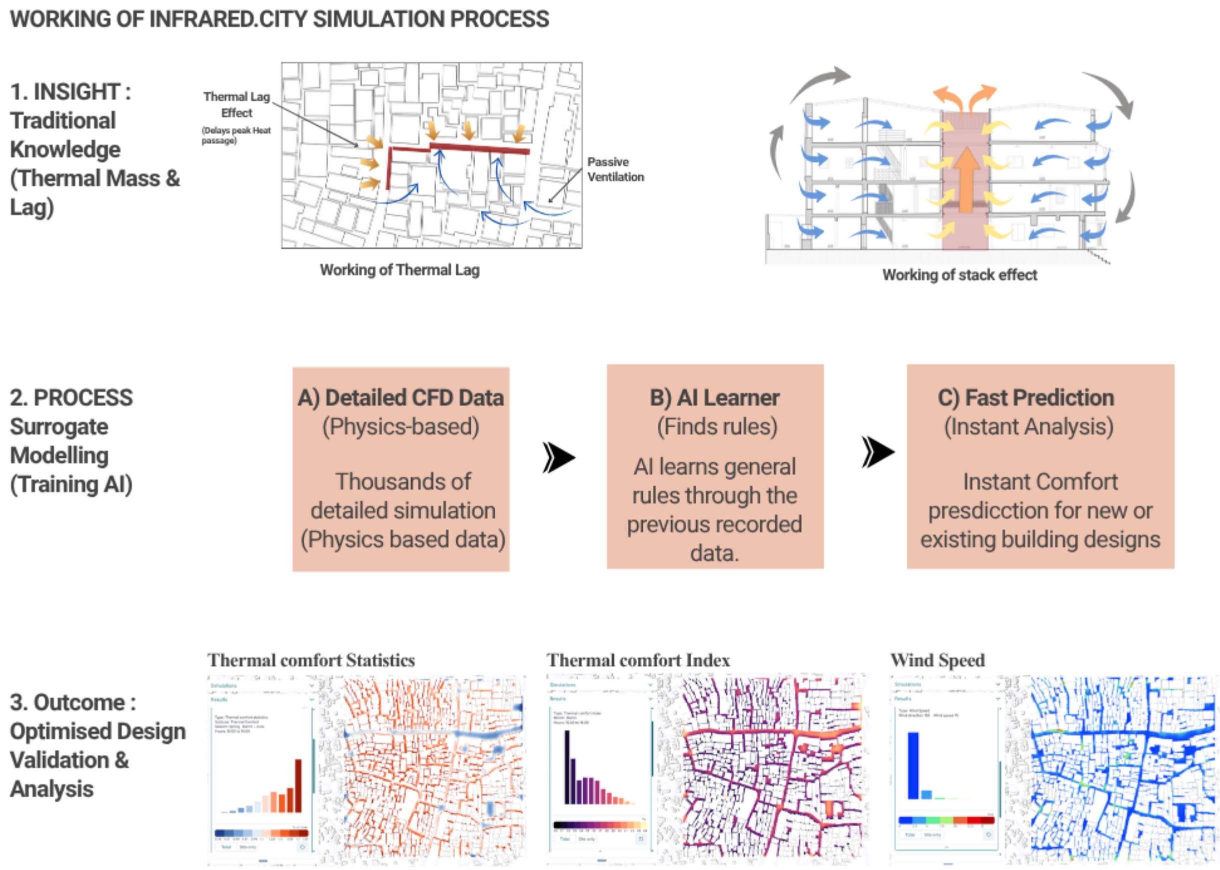


Figure 5 - Diagram showing the working of an AI surrogate model.

<-40	-27	-13	0	9	26	32	38	>46
extreme cold stress	very strong cold stress	strong cold stress	moderate cold stress	slight cold stress	no thermal stress	moderate heat stress	strong heat stress	very strong heat stress / extreme heat stress
Stress Category								

Chart 1 - UTCI stress category Source: From Heat stress indexes explained, by Climateclip and (Fiala, 2011)

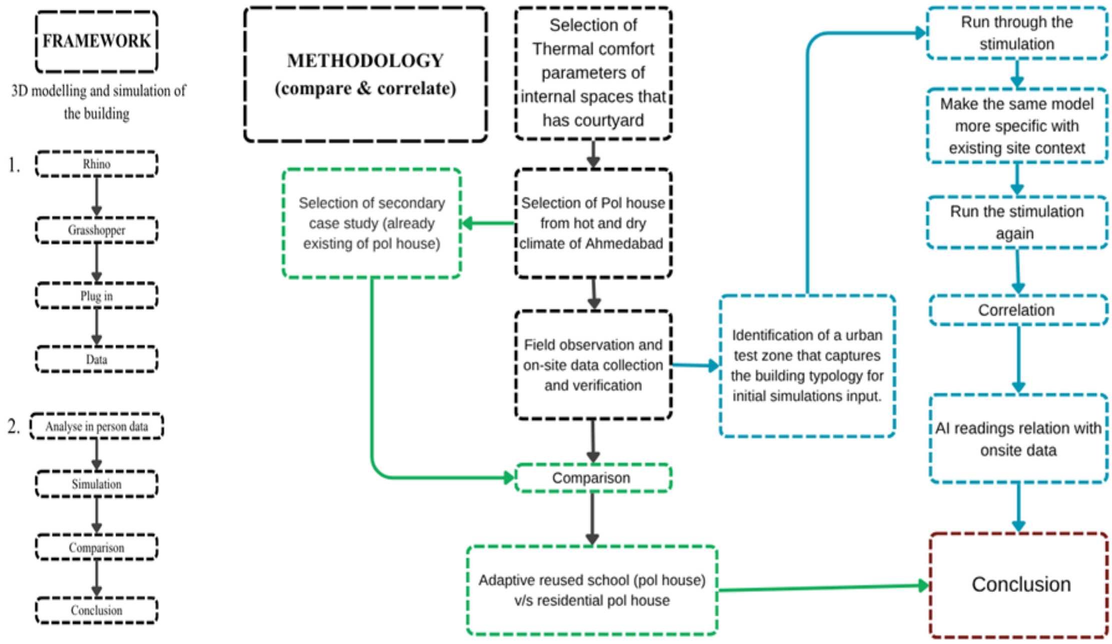


Chart 2 - Framework and method of analysis.

Empirical readings were collected on-site using handheld digital thermometers during active school hours. These readings provide a baseline to calibrate the AI predictions and to identify specific thermal anomalies caused by functional changes. The study specifically looks at the vertical temperature rise across the school's four levels, as high occupancy and modern materials often create heat-trapping zones that are not present in traditional residential Pol houses. By correlating the AI predictions against the hand-collected empirical data points, the research establishes the predictive accuracy of surrogate models for heritage microclimate analysis.

7. Thermal Performance Assessment of an Adaptively Reused Courtyard Building - Case of Unnati School

This research is deeply rooted in the historic city of Ahmedabad, old city, community centric *"Pol"* city (housing system). Unnati School is situated in Jethabhai ni *Pol*, 565, walled City, Khadia, Ahmedabad, Gujarat. The School building (Unnati Balmandir) operates within this fabric, which is a residential building operating with adaptive reuse of it to become a pre - school and a junior primary school. In the context of the walled city, educational institutions often occupy heritage structures like former havelis (elaborately designed residential buildings with central courtyards designed for large and joint families) or large residential mansions that have been adaptively reused.

These structures utilize passive climatic benefits such as thick walls, courtyards, & high ceilings, which provide a comfortable learning environment without heavy reliance on active cooling. These buildings make extensive use of timber elements, which contribute less thermal mass compared to traditional masonry construction. The defining architectural feature of traditional *Pol* houses is the central courtyard, which serves as a critical environmental regulator by facilitating natural daylight penetration and promoting air movement through stack-driven ventilation.

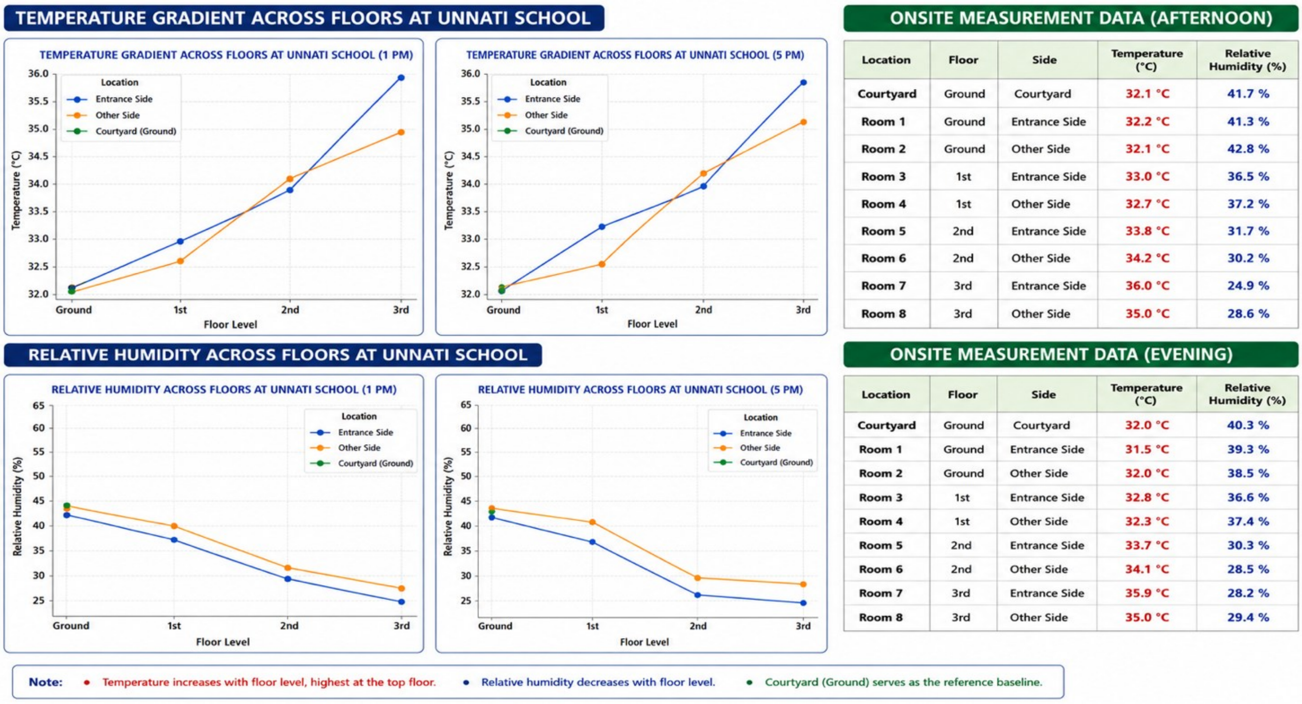
Figures 6 - *Map highlights Unnati School as well as Jethabhai ni pol.*

7.1 Data interpretation

Field measurements revealed a pronounced vertical temperature gradient, with air temperatures increasing by nearly 4°C from the ground floor to the third floor. At the ground level, the courtyard continues to function as a thermal moderator, maintaining relatively stable temperatures of approximately 32°C despite elevated outdoor conditions. However, adaptive reuse interventions, including the introduction of a lightweight steel roof and significantly increased occupancy levels, appear to diminish the effectiveness of the building's traditional passive cooling mechanisms. As a result, the upper floors, particularly the underutilized third floor, exhibit substantial heat accumulation, with temperatures reaching 36°C and relative humidity declining to 24.9%. These findings suggest that while the courtyard retains its cooling influence at lower levels, the altered building configuration and operational demands have disrupted the vertical thermal balance traditionally observed in residential *Pol* houses.

Floor/ level	Class / Group	No. of students
Ground floor	Day care	21
	Junior kg	35
	Senior kg.	40
1st Floor	1st std	38
	2nd Std	38
2nd Floor	3rd std	21
	4th std	13
3rd floor	none	none
Total children	All floor	206 children
Total Faculty	All floors	7 teachers
TOTAL USERS	**ALL floors**	**213 USERS**

Figure 7 - *Plan & section of Unnati school and user group classification table.*



ONSITE MEASUREMENT DATA (AFTERNOON)

Location	Floor	Side	Temperature (°C)	Relative Humidity (%)
Courtyard	Ground	Courtyard	32.1 °C	41.7 %
Room 1	Ground	Entrance Side	32.2 °C	41.3 %
Room 2	Ground	Other Side	32.1 °C	42.8 %
Room 3	1st	Entrance Side	33.0 °C	36.5 %
Room 4	1st	Other Side	32.7 °C	37.2 %
Room 5	2nd	Entrance Side	33.8 °C	31.7 %
Room 6	2nd	Other Side	34.2 °C	30.2 %
Room 7	3rd	Entrance Side	36.0 °C	24.9 %
Room 8	3rd	Other Side	35.0 °C	28.6 %

ONSITE MEASUREMENT DATA (EVENING)

Location	Floor	Side	Temperature (°C)	Relative Humidity (%)
Courtyard	Ground	Courtyard	32.0 °C	40.3 %
Room 1	Ground	Entrance Side	31.5 °C	39.3 %
Room 2	Ground	Other Side	32.0 °C	38.5 %
Room 3	1st	Entrance Side	32.8 °C	36.6 %
Room 4	1st	Other Side	32.3 °C	37.4 %
Room 5	2nd	Entrance Side	33.7 °C	30.3 %
Room 6	2nd	Other Side	34.1 °C	28.5 %
Room 7	3rd	Entrance Side	35.9 °C	28.2 %
Room 8	3rd	Other Side	35.0 °C	29.4 %

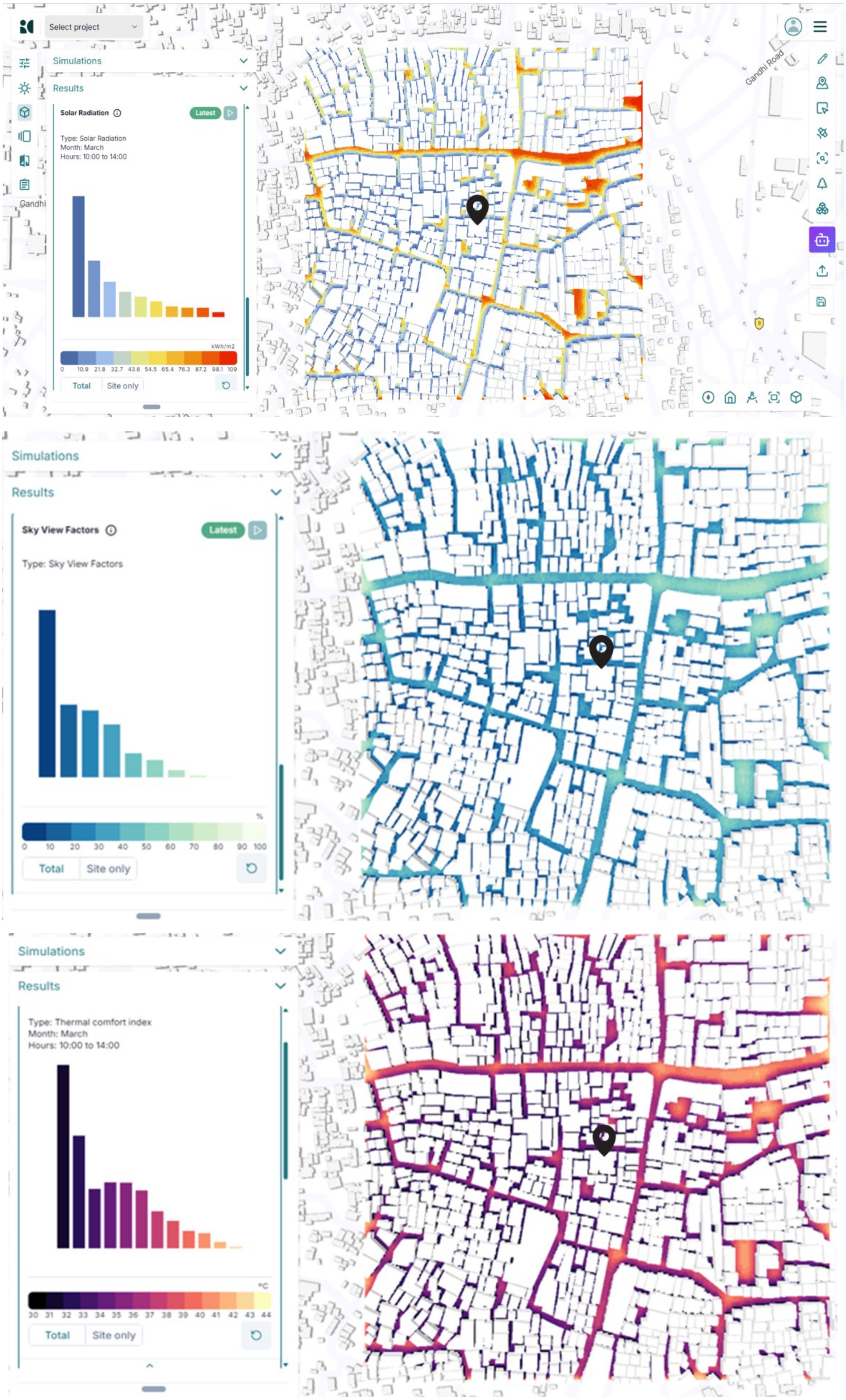
Figure 8 – shows changes in temperature and relative humidity and onsite measurement data.

7.2 Analysis with AI tools

The AI simulation results provide a comprehensive visualization of the site's thermal stresses across an annual cycle. The UTCI Heat map reveals a sustained "Heat Core" from March to October, where values frequently exceed 40°C - 45°C. The Building enters "Extreme Heat Stress" for up to 8-10 hours a day during May and June, leaving a very small window between 3:00 AM and 7:00 AM for the building to purge its stored heat. In January, the building enjoys nearly 70% "No Thermal Stress" (light green zone), making the courtyard an optimal space for daytime activities.

By May, this comfortable window shrinks to less than 20%, replaced by massive bands of "Strong" and "Extreme" heat stress. Interestingly, the simulation shows that in August and September, even if raw temperatures are lower than in May, the surge in humidity traps heat, keeping the occupants in "Very Strong Heat Stress" for longer durations. This highlights the importance of air movement in monsoon months, which is currently inhibited by the covered courtyard at Unnati School.

The simulation also maps the "Golden Hours" of comfort (9°C to 26°C), which are target zones for architectural interventions. In the context of Unnati School, the goal of architectural design should be to expand these green blocks into the "white space" of the charts.


Select project
Simulations
Results
Solar Radiation
Latest
Type: Solar Radiation
Month: March
Hours: 10:00 to 14:00
kWh/m2
0 10.9 21.8 32.7 43.6 54.5 65.4 76.3 87.2 98.1 109
Total
Site only
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Gandhi Road
Simulations
Results
Sky View Factors
Latest
Type: Sky View Factors
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0 10 20 30 40 50 60 70 80 90 100
Total
Site only
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30 31 32 33 34 35 36 37 38 39 40 41 42 43 44
Total
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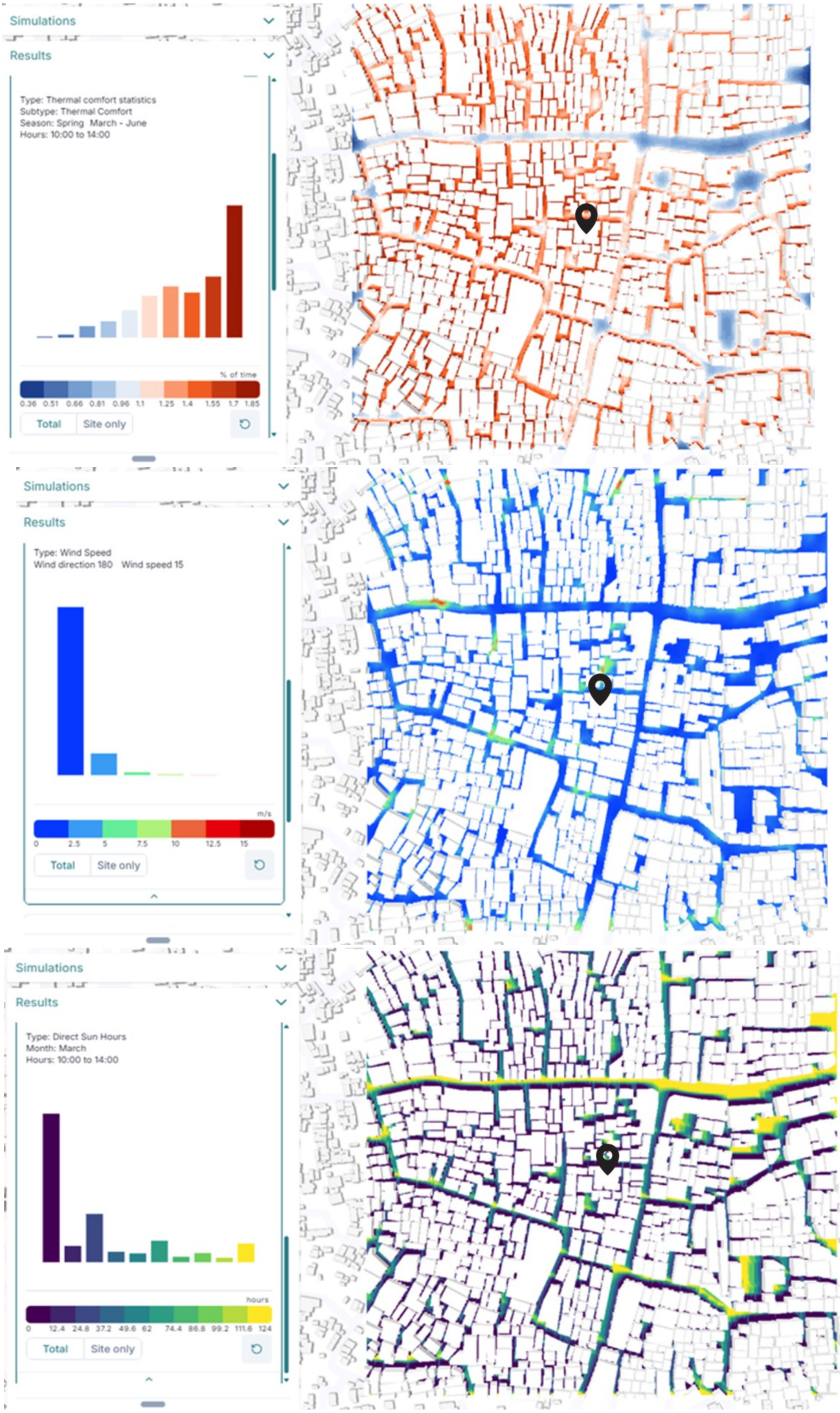

Simulations
Results
Type: Thermal comfort statistics
Subtype: Thermal Comfort
Season: Spring March - June
Hours: 10:00 to 14:00
% of time
0.36 0.51 0.66 0.81 0.96 1.1 1.25 1.4 1.55 1.7 1.85
Total
Site only
Simulations
Results
Type: Wind Speed
Wind direction 180 Wind speed 15
m/s
0 2.5 5 7.5 10 12.5 15
Total
Site only
Simulations
Results
Type: Direct Sun Hours
Month: March
Hours: 10:00 to 14:00
hours
0 12.4 24.8 37.2 49.6 62 74.4 86.8 99.2 111.6 124
Total
Site only

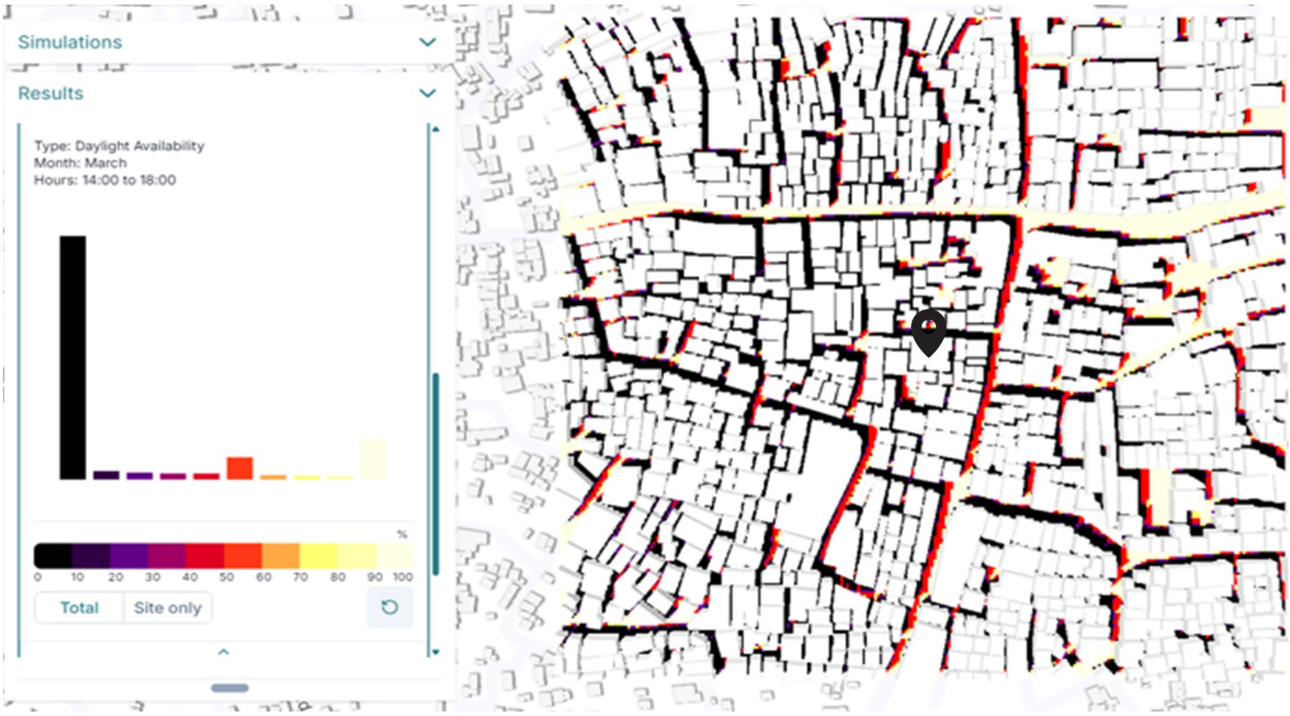


Figure - 9 analysis done using an AI tool on the selected urban cover surrounding Unnati School.

7.3 Comparison

As shown in Figure 1, the primary distinction lies in the airflow mechanism: while the residential Pol utilizes an active stack effect through an open courtyard to achieve a 2°C to 4°C temperature reduction, the school experiences an inhibited stack effect due to its covered courtyard, resulting in a 4°C vertical temperature rise from the ground to the third floor.

The comparison further highlights how occupancy and materials shift the thermal profile; the school faces a much higher internal heat load due to high student density and its steel truss roofing, whereas the residential Pol benefits from the thermal mass of load-bearing brick walls and traditional clay tile roofing. Interestingly, both structures utilise their highest levels, that is an attic in the residential house and the top floor in the school, as buffer spaces to protect lower inhabited zones from direct solar radiation.

A critical component of this research is comparing the results obtained through AI simulations with established literature on traditional *Pol* houses. Studies by (Mihir, 2012) and (Victoria Patricia Lopez-Cabeza, 2022) on residential Pol houses in *Moti Hamam ni Pol* establish a baseline for comparison in this research.

Performance Parameter	Traditional Residential Pol (Vakharia 2012)	Unnati School (Adaptive Reuse)
Thermal Mitigation	2°C to 4°C reduction indoors	4°C vertical rise from G to 3rd floor
Airflow Mechanism	Active stack effect in open court	Inhibited stack effect (Covered)
Primary Heat Source	Rooftop solar radiation	Roof radiation + High internal heat load
Occupancy Pattern	Low density; joint family	High density; intermittent (School hours)
Coolest Zones	Ground floor rooms (31-34°C)	Ground floor courtyard (32°C)
Material	Load bearing brick walls for partitions	Steel I beam on Ground floor
Roof	Clay tiles roofing system	Steel roof (Truss system)
Top Floor	Attic space that acts as buffer space for top floor	Top floor acts as buffer space

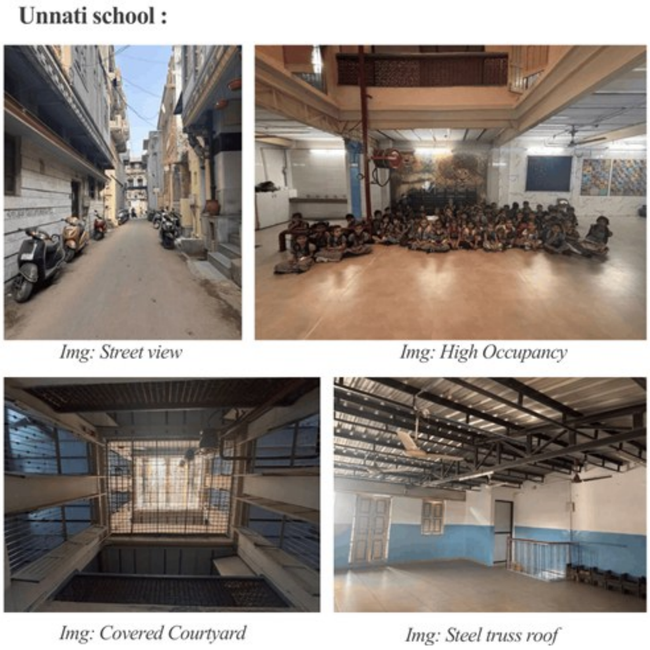


Figure 10 – Comparison between residential and adaptive reuse *Pol* houses.

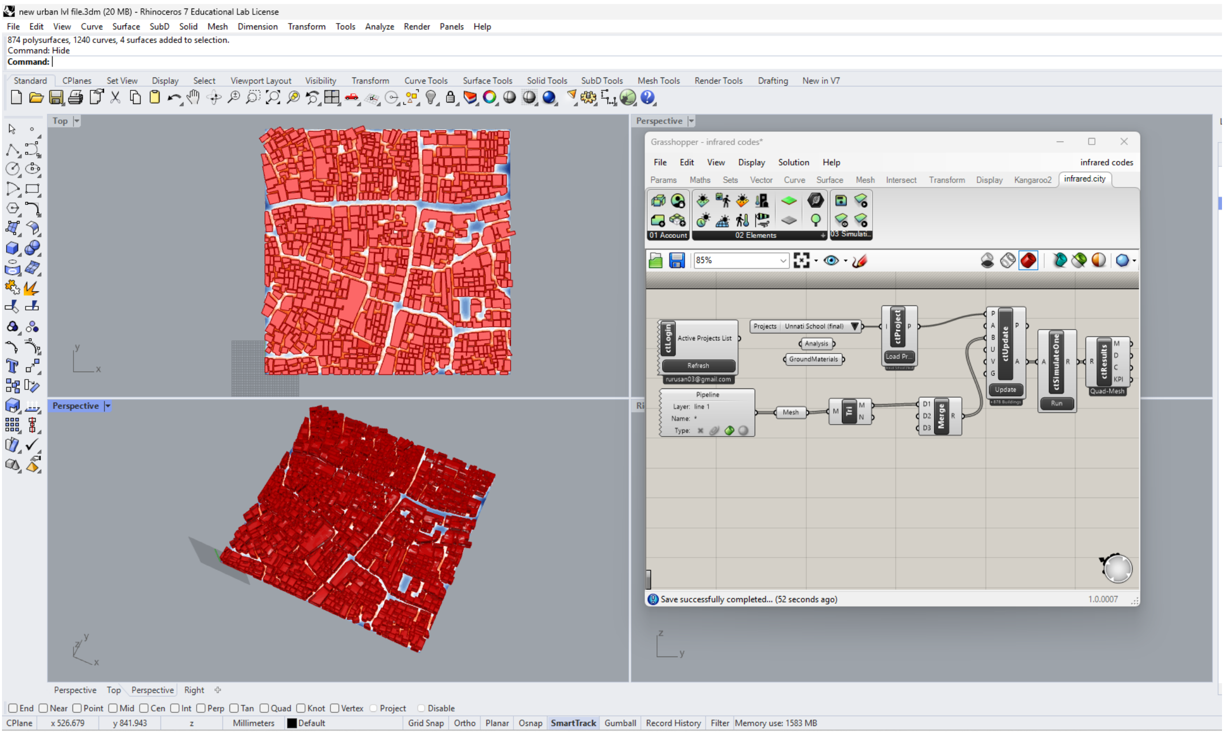


Figure 11 – Rhino, grasshopper and infrared.city plugin interface shows the editing script used to update accurately the selected urban fabric surrounding Unnati school.

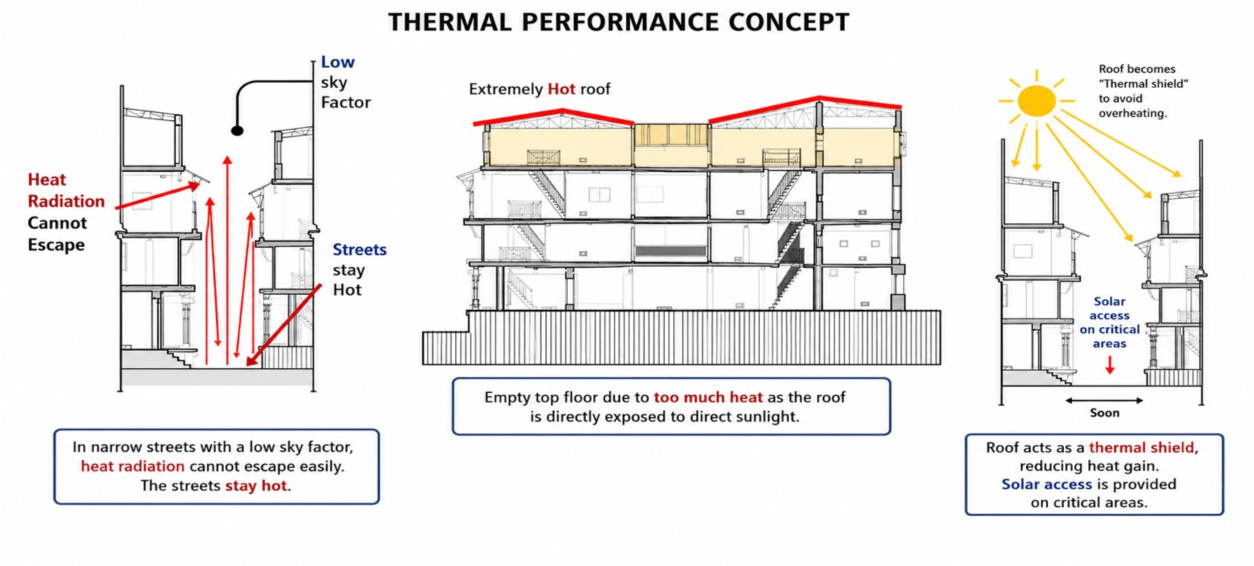
Table 1: Research Findings: Thermal Performance of the Adaptively Reused Pol House.

Finding	Reference / Expected Behaviour	Findings from Unnati School	Interpretation
Ground-floor thermal moderation	Previous research indicates that the courtyard and thermal mass of traditional *Pol* houses contribute to night-time heat dissipation and relatively stable ground-floor temperatures of approximately 31–34°C (Vakharia, 2018)	Field observations and AI-based simulations indicate that the ground floor continues to maintain relatively stable temperatures of approximately 32°C despite elevated outdoor conditions.	The findings suggest that the thermal mass and courtyard configuration continue to provide a degree of thermal moderation despite the building's adaptive reuse.
Roof-driven heat gain	In traditional *Pol* houses, the roof represents an important pathway for solar heat gain.	AI-based simulations identified the roof as a major source of heat gain. However, the simulations did not capture the highly localized vertical temperature increase of approximately 4°C observed between the lower and upper levels.	This indicates that while the AI model can identify broader patterns of heat accumulation, localized thermal effects associated with the lightweight steel roof structure may require field-based validation.
Reduced ventilation within the street canyon	The compact morphology and narrow streets of *Pol* neighbourhoods restrict horizontal airflow and rely substantially on courtyard-mediated ventilation.	Simulations indicated reduced wind movement within the narrow street sections, with wind speeds of approximately 2–3 m/s at selected locations.	The results are consistent with the compact morphology of the *Pol* fabric and indicate the importance of internal courtyards and vertical airflow pathways in maintaining ventilation.

Solar penetration and Sky View Factor	Narrow *Pol* streets and closely spaced buildings limit direct solar exposure at street level.	AI-based UTCI and solar exposure mapping indicated limited direct solar penetration within the narrow internal streets, with these areas exhibiting lower daytime thermal exposure than wider streets.	The compact urban morphology therefore provides substantial daytime shading, contributing to localized thermal moderation.
Interaction between low SVF and heat accumulation	Low Sky View Factor can reduce daytime solar exposure while simultaneously limiting long-wave radiative exchange with the night sky. (Victoria Patricia Lopez-Cabeza, 2022)	The simulations identified high solar exposure on roof surfaces, with peak incident radiation approaching 1000 Wh/m² during the observed period. The low-SVF street environment was associated with limited exposure to the sky.	The findings highlight a thermal trade-off within the compact *Pol* morphology: dense shading can reduce daytime solar exposure but may also constrain nocturnal heat dissipation, particularly under high-humidity conditions.

8. Results

In traditional residential settings, courtyards significantly improve thermal comfort by expelling heat at night and maintaining ground-floor temperatures between 31°C and 34°C. At Unnati School, the ground floor still achieves this "coolth," proving that the high thermal mass of the neighborhood remains a powerful asset. However, the "Thermal Engine" mechanics are disrupted by modern interventions.



Figures 12 – Effect of low Sky view factor; Effect of extreme solar radiation.

In residential Pol houses, the roof was the primary source of heat gain; at Studied building - Unnati School, this is compounded by high occupancy. The AI predictive models effectively capture this shift, showing how the "heat core" at the upper levels is intensified by the combination of the steel roof and the lack of geometric porosity.

The AI-based UTCI mappings were crucial in providing quantitative information on the external forces that the school was undergoing. The AI tool simulations effectively captured the urban cluster canyons of Jethabhai ni Pol, where the dense maze of narrow streets tends to block the penetration of the sun, and is therefore considerably cooler than the wider main roads.

- Wind Stagnation: The AI was useful to simulate a Wind Shadow effect. The heavy G+2 to G+4 building heights provide an impassable barrier to horizontal airflow, reducing wind speeds deep in the Pol streets, to stagnant 2 m/s to 3 m/s. This confirms that the building has to be virtually wholly dependent on internal stack ventilation instead of being cross-ventilated.
- Rooftop Heat Engines: The simulations found building rooftops as the most important "heat engines" of the neighborhood. Although the narrow streets have a low Sky View Factor (SVF) that prevents direct sun exposure, the horizontal roofs experience up to 4 hours of intense direct sun exposure, which peaks at almost 1000 Wh/m2 of radiation.
- The Heat Trap: Since the low SVF does not allow the ground to see the cold night sky, the heat absorbed during the day cannot easily vent away at night and the human body is kept in a state of "Very Strong Heat Stress" even during cooler monsoon evenings when the humidity spikes to 80 percent to 90 percent.

Although the AI successfully mapped these urban-scale "Red Zones," it is observed that the existing voxel-based surrogate models have limitations. The AI was unable to accurately forecast the highly granular, internal, micro-climatic changes, which were highly specific to the school due to the structural changes it had undergone, such as the precise 4°C vertical spike induced by the lightweight steel truss roof.

9. Conclusion

This research has established that the courtyard of the traditional Ahmedabad *Pol* house is neither an architectural ornament nor a passive spatial residue of historic building culture, but a precision-calibrated microclimatic engine whose thermodynamic logic remains empirically demonstrable under the extreme thermal conditions of contemporary architecture. Through the focused investigation of Unnati School within Jethabhai ni Pol, a heritage courtyard dwelling now operating at an institutional occupancy of 213 users, this study has systematically identified the thermal tipping points at which modern adaptive reuse interventions cause measurable, quantifiable deviation from the building's historical passive cooling performance. Empirical monitoring confirms that the ambient protective envelope of the dense Pol urban fabric continues to buffer internal ground-level temperatures at approximately 32°C, a figure significantly below the recorded external summer maxima of 45°C, affirming the enduring efficacy of the vernacular urban form as a thermal regulator. These tipping points, precipitated by the combined thermal burden of high-density occupancy and the replacement of thermally massive traditional roofing with lightweight steel truss construction, are made unambiguously legible by the documented vertical temperature gradient of 4°C within the modified courtyard section, direct physical evidence of the threshold beyond which the courtyard's inherited environmental intelligence is effectively neutralised.

The methodology advanced in this study deliberately bridges vernacular environmental wisdom with contemporary computational synthesis. On-site thermometer readings, which established the critical 32°C ground-level baseline and the 4°C vertical gradient, provided the empirical anchor against which AI-driven simulations, executed via the AI tool platform and computing the Universal Thermal Climate Index, were rigorously verified. This process of empirical calibration was not supplementary to the computational analysis but constitutive of its validity for confirming that AI-driven surrogate modeling achieves research-grade reliability within the complex spatial fabric of the historic Pol, provided geometric inputs are manually refined to faithfully represent the intricate void structure of the heritage tissue. The resulting dataset, combining field-verified UTCI values with urban-scale simulation outputs, provides the most granular thermal portrait of an Ahmedabad Pol microclimate yet produced in the scholarly literature.

Perhaps the most significant methodological contribution of this research is its direct, systematic comparison between the AI-driven simulation approach employed here and the traditional, physics-based Computational Fluid Dynamics methods that have characterised prior heritage microclimate investigations. This comparison is not incidental to the study's findings, it is a deliberately constructed scholarly intervention, designed to evaluate whether rapid AI-driven analysis can deliver analytically equivalent outcomes to the resource-intensive CFD protocols that have historically defined the field. The findings confirm that it can. The AI tool platform identified heat accumulation zones, wind shadow regions, and the precise thermal tipping points within the Pol fabric, including the 4°C vertical gradient distinguishing the thermally compromised upper courtyard from the still-protected ground level at 32°C ,with a speed and accessibility that conventional CFD workflows cannot match at equivalent urban scale. This key contribution advances a methodological reorientation for heritage thermal studies: AI-driven surrogate modeling at the macro scale, empirically calibrated against on-site thermometer readings at the micro scale, constitutes the most operationally viable and analytically robust hybrid protocol currently available for pre-intervention climatic assessment in complex heritage environments. Where CFD remains indispensable for granular interior microclimate resolution, the AI-driven approach demonstrated here democratises access to urban-scale thermal intelligence, rendering it deployable within the practical constraints of standard architectural conservation workflows. At the core of this study's findings is a definitive empirical affirmation of the stack effect as a sophisticated, data-backed passive cooling system. The buoyancy-driven vertical air displacement that the traditional courtyard void was designed to sustain is not a serendipitous consequence of historic construction convention; it is a measurable, quantifiable environmental mechanism that, when structurally intact, maintains internal thermal conditions at approximately 32°C, a differential of 13°C below the 45°C external summer maxima recorded across Ahmedabad. The UTCI analysis conducted through the AI tool platform, verified against on-site thermometer readings, confirms that the urban shield effect of the surrounding Pol morphology continues to provide a fundamental layer of thermal protection at the precinct scale. However, the 4°C vertical temperature gradient documented within Unnati School's modified courtyard section demonstrates unambiguously that this macro-scale protection cannot compensate for the stack effect's disruption at the building scale. Once the courtyard void's vertical capacity for hot air exhaustion is compromised, whether by structural infill, material substitution, or the thermal loading of 213 occupants operating within a space designed for a fraction of that density, the courtyard transitions from a passive cooling asset delivering a 13°C ambient reduction into a heat trap accumulating thermal stress vertically through the occupied section.

The policy implications of these findings are direct and consequential. This research provides an evidence-based foundation for the formal institutionalization of thermal preservation as a statutory conservation criterion within adaptive reuse governance frameworks, positioned alongside structural integrity and aesthetic authenticity as a non-negotiable condition of heritage consent. Thermal impact assessment, utilizing the hybrid AI-driven and empirically calibrated methodology demonstrated in this study, must become a prerequisite for the conversion of low-density residential Pol dwellings into high-density institutional spaces. Immediate remedial interventions at Unnati School, including the physical restoration of courtyard void height to reinstate the vertical air displacement that historically sustained the 32°C ground-level thermal environment, the application of high-albedo cool roof surface treatments to reduce solar heat gain at the uppermost envelope, and the installation of advanced thermal insulation to compensate for the thermal mass lost through steel truss substitution are recommended as urgent first-phase measures within a comprehensive thermal restoration strategy.

The broader significance of these findings extends beyond the specific context of Ahmedabad's Pol neighbourhoods to encompass heritage urban settlements across the Global South confronting the compounding pressures of rapid institutional densification and accelerating climate change. The courtyards of the Pol houses encode centuries of accumulated environmental intelligence, a vernacular thermal response to one of the most climatically extreme inhabited landscapes on earth, capable of sustaining interior conditions 13°C cooler than the surrounding external environment at peak summer. This research proves that the stack effect governing these courtyards is not a historical curiosity but a living, data-backed cooling system that remains a vital and practically deployable solution for protecting heritage buildings, and the vulnerable populations within them, in our warming climate. Preserving that system structurally, materially, and spatially is not an act of architectural nostalgia. It is an act of environmental necessity.

Beyond evaluating a single building, this study contributes to the broader discourse on heritage conservation and climate adaptation by exploring how traditional environmental knowledge systems can be retained and reinterpreted in contemporary uses. As increasing numbers of heritage buildings are adapted for schools, community facilities, and other public functions, understanding their thermal performance becomes essential for developing evidence-based adaptive reuse strategies that balance occupant comfort, heritage value, and environmental sustainability.

The findings suggest that AI-enabled simulation platforms such as AI tool have significant potential for assessing thermal comfort in built environments. While their predictive capabilities are expected to improve with enhanced datasets and model development, AI-generated outputs should currently be validated against field measurements and conventional simulation methods to ensure reliability. By enabling rapid environmental assessments and reducing computational demands, AI-assisted tools offer valuable opportunities for academia, supporting research in climate-responsive architecture, heritage conservation, and urban thermal comfort.

Conflicts of Interest

The authors declare no conflict of interest.

Data Availability Statement

All datasets are included within the article

Institutional Review Board Statement

Not applicable

Credit Author Statement

All authors have read and approved the final version of the manuscript.

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