Significance of Building Orientation of Institutional Buildings with Vernacular Elements: A Mathematical Analysis

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Abstract

Vernacular buildings use indigenous materials and construction techniques that are region-specific to enhance natural ventilation, daylight progress, and thermal comfort inside the buildings. In this study, a mathematical model has been developed to predict the room/corridor temperature distribution in preferentially oriented (-45° North) vernacular spaces in southern India.

The research employs a mathematical approach to study such buildings. It measures the shadow area yield, room temperature, daylight progress, and corridor temperature over time using field experiments, and the same have been validated with building simulations. Solar analysis has been carried out to assess the degree of daylight progress inside a classroom as a function of window placement and window opening size.

The daylight progress inside the classroom is found to depend on the window placement and window opening size. The building simulation results indicate a differential heating phenomenon inside the vernacular spaces viz., the eastern part of the building heats up faster than its western counterpart. Furthermore, the corridor/room temperature profiles obtained from the experiments and simulations mimic a cubic function, with minor deviations.

Keywords: Vernacular; Orientation; Mathematical model; Building simulation; Indoor; Lighting.

Introduction

Vernacular architecture is a mirror reflecting the cultural, environmental, and social values of a community. Among the many factors shaping vernacular spaces, building orientation stands out as a pivotal element. Recently, the world has shifted its focus towards constructing energy-efficient buildings (Zhang *et al.*, 2006; Kabir, Sadiq and Tesfamariam, 2014; Soewarno, 2014; Monga and Das, 2018). Energy-efficient buildings are meticulously planned settings that offer occupants the highest level of thermal comfort while minimizing energy usage. Number of countries have made it mandatory for builders to obtain energy performance certification (EPC), with the goal of promoting energy-efficient building practices in their respective regions (Dascalaki *et al.*, 2013; Parkinson *et al.*, 2013; Herrando *et al.*, 2016; Aydin, Correa and Brounen, 2019; Qiu and Kahn, 2019). Although government policies are in place, energy consumption in buildings continues to be on the rising side (Pérez-Lombard, Ortiz and Pout, 2008; Iwaro and Mwasha, 2010; Bilgen, 2014; Allouhi *et al.*, 2015; Gul and Patidar, 2015). If one takes a closer look at the literature, majority of authors highlight following reasons for higher energy consumption in buildings; (i) wrong choice of construction materials and (ii) poor construction design (Koushki and Kartam, 2004; Binici, 2007; Marzouk, El Kherbawy and Khalifa, 2013).

It is clear from their work that, even after changing the design and construction materials, there is no significant improvement in the thermal comfort index values (Tombesi, 2006; Binici, 2007; Wekesa, Steyn and Otieno, 2010; Ivkovska, 2020; Albabely and Alobaydi, 2023; Ishrat *et al.*, 2023). Hence, something must be fundamentally wrong with our assumptions while doing the experiments/simulations. One such parameter that is important, but found missing in the literature is; how the building would perform, when its orientation changes with respect to its true north axis? The answer of course lies in the Vernacular.

Looking at the literature, only a handful of authors have considered, building orientation as a parameter, in their experiments for assessing the micro-climatic conditions (Salazar Trujillo, 1998; Village, 2019; Fawzi Al-Nuaimi and Maki Mohammed, 2022; Kordhaghi, Zolfaghari and İnceoglu, 2022; Ali, Asmal and Amin, 2023; Saraswat, Pipralia and Kumar, 2024). This information is critical during the design stage, as it is going to decide the degree of daylight progress, wind flow, relative humidity, (Gulyás, Unger and Matzarakis, 2006; Wong, Jusuf and Tan, 2011; Dimoudi *et al.*, 2013) shadow area, etc., inside the built space.

A comprehensive literature survey investigating the impact of building orientation on the vernacular spaces reveal a multifaceted relationship between orientation strategies and environmental performance (Monga and Das, 2018; Village, 2019). Studies underscore the significance of orientation in optimizing natural light penetration, thermal comfort, and energy efficiency within educational environments rooted in vernacular architectural traditions (Albabely and Alobaydi, 2023). Furthermore, research highlights the cultural and contextual considerations influencing orientation decisions, elucidating the interplay between climatic factors, spatial organization, and pedagogical requirements in the design and utilization of such spaces (Kordhaghi, Zolfaghari and İnceoglu, 2022).

Rapoport has clearly pointed out that vernacular architecture is deeply rooted in its context, embodying the wisdom of generations. Building orientation, thus, is not a mere option but a deliberate choice informed by environmental factors, cultural beliefs, and functional necessities (Rapoport,1969). Oliver further accentuates this by emphasizing that the orientation of vernacular buildings is intrinsically linked to climatic considerations, harnessing natural elements like sunlight and wind to ensure comfort and sustainability (Oliver,1989). The significance of building orientation extends beyond pragmatic concerns to encompass cultural symbolism and societal norms. As noted by Nasar and Terzano, the orientation of vernacular structures often reflects religious beliefs, with buildings aligned to face sacred sites or in accordance with rituals (Nasar & Terzano, 2010). In this way, building orientation becomes a tangible expression of cultural identity and spiritual connection.

Indeed, vernacular architecture epitomizes adaptation to local environments, and building orientation plays a pivotal role in this regard. According to Hassan Fathy (1981), vernacular dwellings are ingeniously oriented to mitigate climatic extremes, maximizing shade in hot climates and harnessing solar gain in colder regions. Such adaptive strategies not only ensure comfort but also underscore the sustainable ethos inherent in vernacular design (Hassan fathy,1981). Beyond its functional and environmental implications, building orientation in vernacular architecture is intertwined with social dynamics and communal life. As highlighted by Moughtin et al. (1999), the layout and orientation of vernacular settlements often foster social cohesion, with public spaces and pathways strategically integrated to facilitate interaction and communal activities.

Thus, building orientation becomes a catalyst for fostering a sense of community and collective identity (Moughtin *et al.*, 1999). In the face of rapid urbanization and modernization, the significance of building orientation in vernacular spaces faces unprecedented challenges. As Mehta and Pal (2018) argue, indiscriminate adoption of Western architectural norms often leads to the neglect or destruction of vernacular building traditions, eroding cultural heritage and exacerbating environmental issues. Preserving the significance of building orientation in vernacular spaces necessitates a holistic approach that integrates traditional knowledge with contemporary design principles (Mehta and Pal, 2018).

This ideology has been deeply rooted in vernacular buildings produced by the locals, for centuries. To do so, the role of the sun path on the micro-climatic conditions inside a building needs to be understood constructively. Only then, a building can respond to climate change effectively.

Further to support this philosophy, Yuling and Xiaohua have developed a mathematical model to improve the thermal performance of a retrofitted vernacular building by imbibing the climate theory (Blengini, 2009; Zhou *et al.*, 2016; Fan and Xia, 2018; Diz-Mellado *et al.*, 2021; Jonkutė *et al.*, 2021). They have shown that building orientation plays a vital role in deciphering the air temperature dynamics inside the living rooms (Zhou *et al.*, 2016). This eventually will affect the micro-climatic conditions in the living space, viz., occupants' health insight, work outputs, environmental responsibility, etc. Studies also show that experimental models using machine learning techniques can also help the design of such buildings (Kariminia *et al.*, 2016; Li *et al.*, 2019; Alonso and Renard, 2020).

In this context, this study aims to understand the importance of orientation on the vernacular buildings and how they modify the micro climatic conditions surrounding them. Objectives of this study are as follows:

1. To understand the importance of orientation on the shadow area evolution, room/corridor temperature dynamics, and daylight progress inside the vernacular spaces.
2. To identify the degree of shadow area variation and its impact on the courtyard temperature evolution is also discussed.
3. To validate the differential heating phenomenon inside classrooms using extensive building simulations using IES-ve.
4. To ascertain the role of building orientation on the air temperature progress inside the classrooms as a function of window placement and opening size, using Autodesk Revit.

Theoretical Framework

Exploring how building orientation can alter vernacular architecture involves considering various theoretical perspectives from fields such as architecture, anthropology, environmental psychology and environmental design. Here are some relevant theories that could support our study:

(i) Climatic Design Theory

This theory focuses on designing buildings and spaces in response to local climatic conditions. It emphasizes the importance of considering factors such as solar orientation, wind patterns, and temperature variations in architectural design. In the context of vernacular architecture, climatic design theory can help explain how building orientation is adapted to optimize natural ventilation, daylighting, and thermal comfort in different climates. In a review article, Santamouris *et. al.* provides an overview of heat transfer phenomena on building envelopes by including the influence of climatic factors on heat transfer coefficients. It discusses the importance of considering climatic conditions in building design to optimize thermal performance and energy efficiency (Santamouris, *et al.*, 2018). They offer insights into the application of Climatic Design Theory in various aspects of building design, construction, and performance evaluation. They highlight the importance of considering climatic factors in architectural and engineering practice to create environmentally responsive and energy-efficient built environments.

(ii). **Bioclimatic Design Theory**

Bioclimatic design theory builds on climatic design principles but also considers the biological and ecological aspects of the environment. It emphasizes strategies for sustainable building design that minimize energy consumption, reduce environmental impact, and promote human well-being. In vernacular architecture, bioclimatic design principles may influence building orientation to maximize passive solar heating, minimize heat gain, and enhance natural ventilation. Banerjee & Koenigsberger have also discussed various bioclimatic design principles for low-cost housing in developing countries, emphasizing strategies to enhance thermal comfort and energy efficiency while minimizing construction costs. It explores the application of passive design techniques and appropriate building materials to create sustainable and livable housing solutions (Banerjee & Koenigsberger 1980). They offer valuable insights into the principles and application of Bioclimatic Design Theory in architecture. They provide theoretical frameworks, case studies, and practical guidance for designing environmentally responsive and energy-efficient buildings that enhance occupant comfort and well-being while minimizing environmental impact.

(iii) **Anthropological Theories of Space and Place**

Anthropological theories of space and place explore how cultural beliefs, practices, and social interactions shape the built environment. These theories highlight the cultural significance of architectural elements, spatial layouts, and building orientations in different societies. In the context of vernacular architecture, anthropological perspectives can help elucidate how building orientation reflects cultural values, social organization, and traditional knowledge systems within specific communities. Low (2003) examines the cultural, social, and psychological dimensions of gated communities in the United States, drawing on anthropological theories of space and place. He explores how gated communities embody social divisions, anxieties about crime and security, and aspirations for privacy and exclusivity, illuminating broader issues of inequality and urban fragmentation (Low, 2003). In fact, he offer insights into Anthropological theories of Space and Place, exploring how cultural meanings, social practices, and power dynamics shape the production and interpretation of space and place. They provide theoretical frameworks and empirical studies that illuminate the cultural construction of space, the embodied experience of place, and the social dynamics of spatial organization and representation.

(iv) **Environmental Psychology**

Environmental psychology investigates the psychological and behavioral responses of individuals to their built environments. It examines how factors such as spatial layout, natural lighting, and indoor-outdoor connections influence human perception, mood, and well-being. In vernacular architecture, environmental psychology can shed light on how building orientation affects occupants' experiences, comfort levels, and sense of connection to the surrounding environment. In this connection, Kaplan (1995) proposes an integrative framework for understanding the restorative benefits of nature on human well-being. Kaplan discusses how exposure to natural environments can enhance cognitive functioning, reduce stress, and promote psychological restoration, highlighting the importance of incorporating natural elements into built environments to support human health and well-being (Kaplan, 1995). They offer insights into the interdisciplinary field of Environmental Psychology, exploring how psychological theories and methods can inform the study and design of built and natural environments to enhance human well-being, behavior, and sustainability.

(v) **Socio-Spatial Theory**

Socio-spatial theory explores the relationship between social processes and spatial configurations within built environments. It considers how social dynamics, power relations, and cultural practices shape the organization and use of space. In vernacular architecture, socio-spatial theory can help analyze how building orientation reflects social norms, kinship structures, and community identities, and how it facilitates or constrains social interactions and activities. Dear and Flusty (1998) explore the implications of postmodernism for urban theory and practice, discussing how socio-spatial relations are reconfigured in the context of globalization, neoliberalism, and cultural fragmentation. They examine the fragmentation of urban space, the rise of new forms of social exclusion, and the challenges of governing diverse and contested urban landscapes (Dear & Flusty, 1998)). While they may not explicitly use the term "Socio-Spatial Theory," they engage with concepts and perspectives that are central to socio-spatial analysis and offer valuable insights into the intersection of social and spatial dynamics in contemporary society.

Based on the abovesaid theoretical perspectives, one can understand how building orientation influences the design, function, and cultural significance of vernacular architecture across different contexts. These theories provide the conceptual frameworks for analyzing the complex interplay between environmental, social, and cultural factors in shaping architectural form and spatial experience.

Review of Literature

There are many studies that look at orientation and thermal issues. For example, Ozbek (2018) has explored the relationship between building orientation and thermal comfort in traditional Turkish houses. Using computational simulations and field measurements, he analyzes how variations in building orientation affect indoor temperatures and energy performance. The findings highlight the importance of considering vernacular design principles for optimizing thermal comfort and energy efficiency in contemporary architecture. Similarly, Yassin *et. al* (2020) have investigated the design strategies and environmental principles underlying traditional courtyard houses in Yemen. Through field surveys and environmental analysis, they examine how building orientation, spatial layout, and passive design features contribute to natural ventilation, daylighting, and thermal comfort. They provide insights into the sustainable design principles of vernacular architecture in hot arid climates (Yassin et al., (2020).

Al-Kodmany has examined the role of building orientation and form in traditional Middle Eastern architecture. Drawing on case studies from the region, he discusses how cultural, climatic, and environmental factors influence building orientation patterns and spatial organization. He highlights the adaptive design strategies of vernacular architecture and their relevance for contemporary sustainable design practices (Al-Kodmany, 2017).

It is well known that in his seminal work, Hassan Fathy has explored the principles of vernacular architecture in rural Egypt. Through case studies and design examples, Fathy illustrates how building orientation, materials, and construction techniques are tailored to local climatic conditions and cultural traditions. He emphasizes the social and environmental sustainability of vernacular architecture and its potential for addressing contemporary housing challenges (Fathy, 2000). Finally, Olgyay et al. (1963) present a bioclimatic approach to architectural design, emphasizing the relationship between climate and building form. They discuss how vernacular architecture incorporates passive design strategies to achieve thermal comfort and energy efficiency. Drawing on case studies from around the world, they provide insights into the role of building orientation, shading, and ventilation in vernacular building design (Olgyay & Olgyay 1963).

These discussions collectively offer valuable insights into the ways in which building orientation influences the design, performance, and sustainability of vernacular architecture across different cultural and climatic contexts. They demonstrate the importance of integrating traditional design principles with contemporary architectural practices to create environmentally responsive and culturally appropriate built environments.

Research Methodology

Geographical Description

This research employs a case study from Tiruchirappalli which is located in the southern part of India, in the Tamil Nadu province. It is geographically located at 10.8050º N and 78.6856º E. Tiruchirappalli is also the geographic epicenter of Tamil Nadu. The topographical condition of Tiruchirappalli is flat with few hillocks like Golden Rock, Rockfort, etc., made up of cretaceous rocks of the Trichinopoly group. The city can be broadly divided into the cantonment area in the south, temples in the north, the bazaar in the city center, and the industrial/educational hub along the east. This study focus is limited to the eastern part of Tiruchirappalli, as the site is located on the Tiruchirappalli-Thanjavur highway (NH-83). It is on the highway where the National Institute of Technology Tiruchirappalli (NITT) is located. The institute spans over eight hundred acres and offers a perfect ecosystem for professional education. The location of the study area from a global perspective is shown in the Fig. 1.

Fig. 1: The location of Architecture block, NIT Tiruchirappalli
Source: Author

Climate

According to Koppen-Gieger, Tiruchirappalli experiences a warm-humid climate and comes under “Aw” type of climate classification. During rainy season it is oppressive and overcast, while the summer is muggy and partly cloudy. The city is hot throughout the year, while the peak summer is experienced from March to June. The average temperature of Tiruchirappalli is 28.6º C, while the average rainfall is about 82 cm. Tiruchirappalli experiences rainfall from the southwest monsoon (June - September) and the northeast monsoon (October - November). Among the two, the northeast monsoon is more prominent than that of the southwest monsoon. As Tiruchirappalli is in the northern hemisphere, the hottest month of the year is May, during which the sun travels east to west via north. Air temperature (A.T), relative humidity (R.H) and wind velocity (W.V), values fluctuate as follows; 20 to 42º C, 32 to 94 %, and 1 to 12 m/sec respectively. Field experiments were done on 5th March, during the driest month of the year. The sun path diagram for the true North and -45° North oriented building is presented in Fig. 2. Numbers “01 to 06” in Fig. 2 indicate the room numbers in sequential order, while the letter “C” represents the courtyard space of a true North and -45º North oriented building. From this diagram, the shadow area swept by the courtyard in the true North and -45º North oriented building was calculated as a function of time, 8 am to 5 pm. The sun path diagram conforming to 5 March 2020 (8 am to 5 pm) was downloaded from *http://www.andrewmarsh.com/*.

Offline, this research used AutoCAD 2018 software to calculate the shadow area information. And using this information, the shadow area variation rate (as a function of time) in the true North and the -45º North oriented building was calculated.

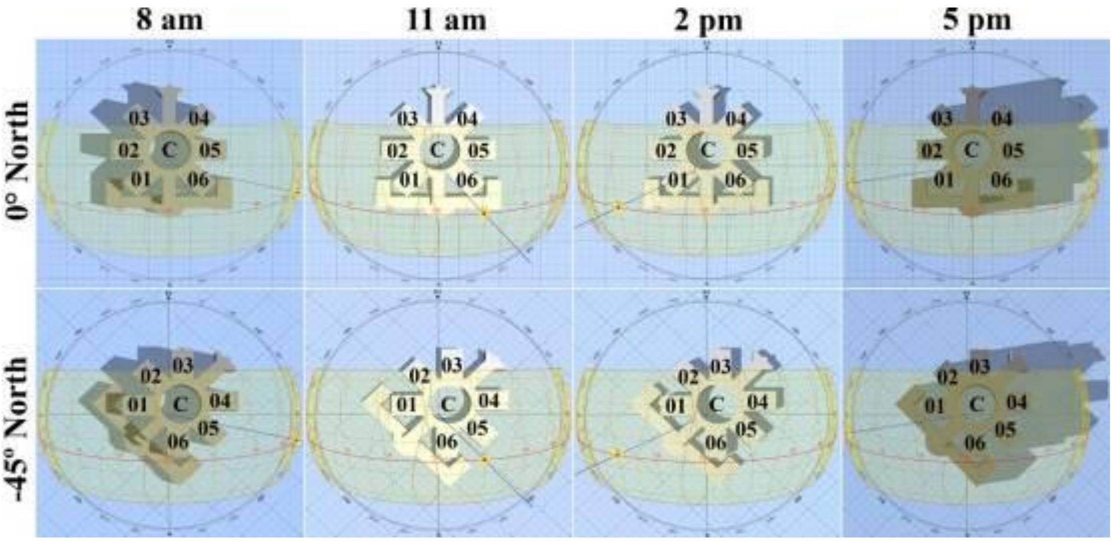

Fig. 2: Sun path diagram of the true North and the -45º North oriented DoA building.
Source: *http://www.andrewmarsh.com/*

Site Details

A 3D view of DoA with its sectional view is presented in Fig. 3. The building has been intentionally oriented to -45º North, so that it is parallel to NH-83.

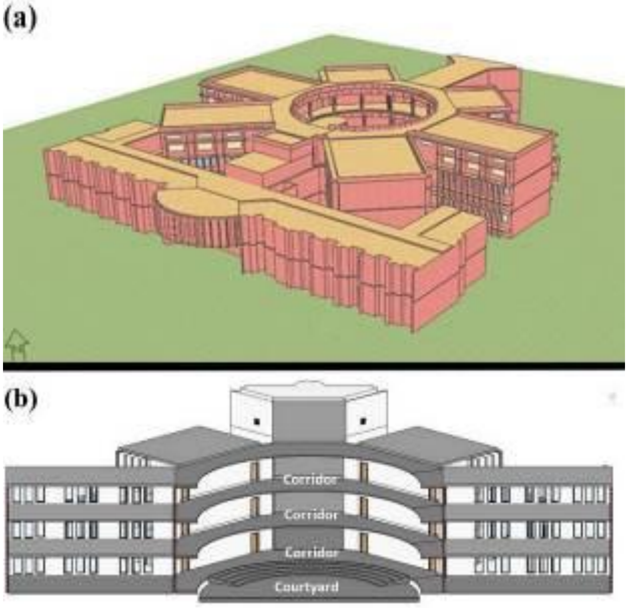

Fig. 3: 3D models of the Department of Architecture, NIT Tiruchirappalli
Source: Author

The Department of architecture, NIT Tiruchirappalli have been designed by considering vernacular features which are presented in the Fig. 4. The external wall of the building is 0.3 m thick (brick wall), with horizontal and vertical slits of 0.15 m thick (concrete masonry units). To prevent the hot air progress inside the classrooms via the window openings, the windows are bounded by slits whose sole purpose is to block the hot air entry inside the classrooms. The department encompasses classrooms in three levels viz., ground, first, and second floor levels, with a circular courtyard of 12 m radius which allows the movement of hot air through stack effect. The courtyard is flanked by a 3 m wide corridor, which acts as a buffer space preventing the hot air from the courtyard the penetrate inside the rectangular classrooms of 12 m x 18 m. The total height of the classroom is 4.95 m with window openings on the northern and southern side. Each window encompasses a translucent glass of 0.25 solar heat gain capacity (SHGC). Both, the southern and northern side has a clerestory window opening of 1.2 m high. Below the clerestory windows are the normal casement windows of 1.2 m and 0.6 m high which corresponding to the northern and southern side of the classrooms respectively which is shown in Fig. 4.To favor the northern light inside the classrooms, the windows placed on the northern side are provided with a larger opening than its southern counterpart. All the windows are flanked with vertical slits in the ground and first floor levels.

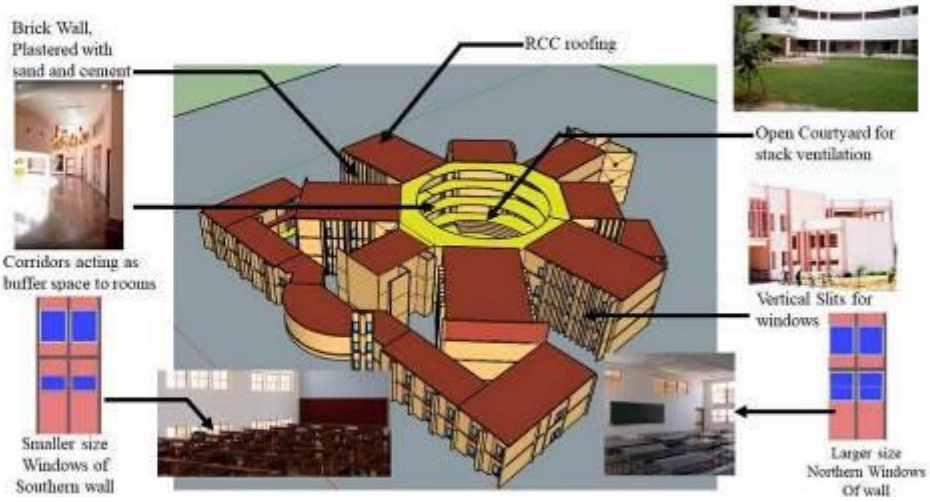

Fig. 4: Vernacular Features of Department of architecture, NIT Tiruchirappalli
Source: Author

To understand the effect of building orientation on the air temperature dynamics inside the classrooms, it is wise to have a fair picture of the building itself in the true North and -45º North orientations. Fig. 5 (a) and (b) show the 2D illustration of true North and -45º North oriented buildings, respectively. The letter "C" displayed in the center of Fig. 5 (a) and (b) indicates a circular courtyard, while its perimeter is highlighted in blue and maroon color. The classrooms associated with the courtyard are arranged chronologically (from "01" to "06") from the entrance (A or A'), while their entry and exit are indicated using A and B & A' and B' respectively. Fig. 5 (a) indicates an imaginary/ideal design space using which DoA, NITT should have been built so that the building axis (A-B) is parallel to North-South axis. Since the building is not going to be parallel to the NH-83 if we orient it that way (as shown in Fig. 5 (a)), it was decided to orient the building axis by -45º w.r.t the North (A'-B') as shown in Fig. 5 (b). As it is evident from Fig. 5 (b), upon orienting the building axis from A-B to A'-B'; the DoA, NITT has been made parallel to NH-83. To provide a better understanding between the true North and -45º North oriented building, maroon and blue colors have been used to distinguish the perimeters of true North and -45º North buildings. Here the N', E', S', W' are the axes of -45º North oriented building (maroon color axes) while N, E, S, W are the axes of an ideal/imaginary (true North) building.

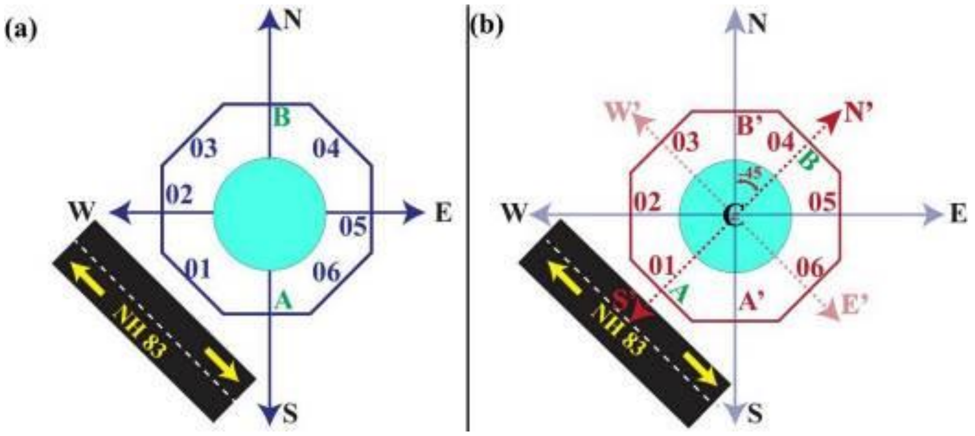

Fig. 5: Top view of the DoA, NITT building in (a) true North and (b) -45º North orientation.
Source: Author

Experimental Procedure

This research explores the role of building orientation on the air temperature progress inside the classrooms via window openings, using Autodesk Revit. It carries out extensive building simulations using IES-ve is done to validate the differential heating phenomenon inside the classrooms.

Experimental work can be broadly classified into two aspects, (i) field experiments and (ii) the building simulations using IES-ve. In the first part, two classrooms (one from the east and another from the west side of the building) were selected randomly from each floor. Subsequently, air temperature (AT) in the corridor and classrooms were measured using a Heat stress index system supplied by M/s. Extech, USA. Experiments were done on March 5th 2020 from 8 am to 6 pm, and the data was recorded for every 3 hrs. The measurements were taken on the corridor and inside the classrooms by closing the clerestory windows and opening the casement windows. Five readings were taken inside the classrooms 1.2 m from the base level, which is highlighted in blue (on the corridor) and pink color (inside the classrooms), as shown in Fig. 6.

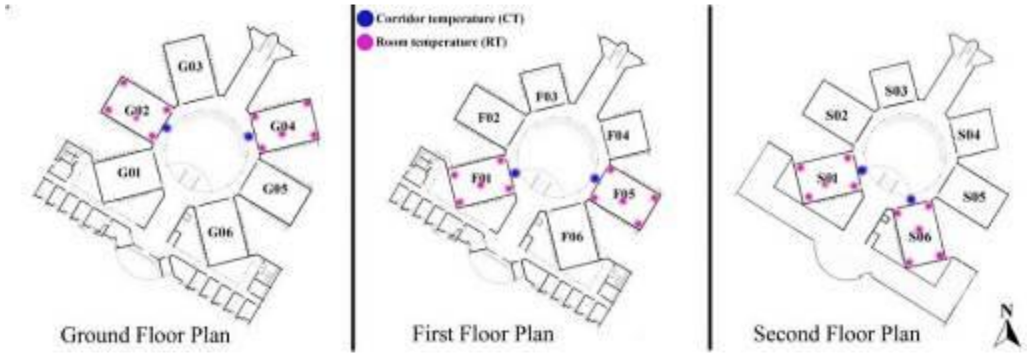

Fig. 6: Point of measurement in the corridor(s)/room(s) of G2, G4, F1, F5, S1, and S6.
Source: Author

Table 1: Climatic variables considered in IES-ve for calculating air temperature distribution in corridor and room spaces
Source: Rawal *et al.*, 2016; Doctor-Pingel *et al.*, 2019

Classroom	Air temperature (˚C)	Relative humidity (%)	Wind velocity (m/s)	Metabolic rate (J/s)	Clothing index
G02	31.6	51.80	0.05	1	1
G04	32.5	45.00	0.11	1	1
F01	32.2	43.50	0.30	1	1
F05	32.6	44.80	0.06	1	1
S01	32.6	44.50	0.23	1	1
S06	32.9	45.90	0.04	1	1

CFD Simulation

The experimental work was validated using computational fluid dynamics simulation with the help of IES-ve software. A 3D model of DoA was developed using "ModelIT" module in IES-ve. Subsequently "Apache" module was used to run the air temperature related simulations for the entire building. Based on the "Apache" simulation, the boundary conditions were fixed for CFD simulations using "VistaPro" module in IES-ve. Matrix spacing and merge tolerance used to perform CFD simulations were 1e−4 m and 1e−5 m, while the number of superficial repetitions was fixed to 500. Finally, using the "MicroFlo" module, the air temperature distribution in the corridor/classrooms were estimated using IES-ve. CFD simulations were done based on ASHRAE 55 standard. The input variables used to validate the air temperature distribution in the corridor and classrooms are discussed in Table 1.

Further, Autodesk Revit 2023 was used to build a 3D model of DOA NITT and subsequently solar analysis was performed using Revit Insight 2023 plugin. Motive behind the solar analysis is to understand how the solar heat gain varies in different levels as a function of building orientation. Autodesk Revit Insight uses Perez solar model to comprehend our problem in a graphical sense. The floors in different levels were selected and the following sun settings were used as shown in Table 2.

Table 2: Parameters used for solar analysis in Revit Insight 2023

S. No.	Solar analysis parameters	Conditions/Settings
1	Solar Study	Single day
2	Presets	Summer solstice solar study
3	Day of analysis	05-03-2019
4	Location	Latitude: 10.7905° N, Longitude: 78.7047° E
5	Time period of solar analysis	8 am till 6 pm
6	Level	GF, FF, and SF
7	Type of solar analysis	Cumulative insolation
8	Units	kW/hr
9	Graphical display style	Solar analysis default

Results

To understand the impact of building orientation on the air temperature dynamics in the corridor(s) and classroom(s), CT and RT measurements were made over time, as illustrated in Fig. 7. The red and green color lines in Fig. 7 represent RT and CT, respectively. Irrespective of the floor levels, RT mimics CT over time, but their magnitudes vary considerably. To comprehend the impact of floor levels on the magnitudes of CT and RT, the rate at which room and corridor temperatures vary (between 8 am and 2 pm) is computed from Fig. 7 and is presented in Table 3. It is clear from Table 3 that the corridor gets heated up faster than their respective classrooms. Although this is an expected outcome, harmonious heating of the courtyard and corridor could make a huge difference in perturbing the air temperature dynamics inside the classrooms, as such. For example, the rate at which CT/RT increases in G4 is higher (eastern side) than that of G2 (western side). Similar analogy holds true for the classrooms positioned in the first and second floor levels (Fig. 6 and Table 3). The rate at which CT/RT increases is higher in the eastern side, than its western counterpart. Based on the climate theory, the trend should be opposite to what we have got in Table 3. Which is, the corridors/classrooms located on the western side must have heated up faster than the corridors/classrooms in the eastern counterpart? Since the DoA building axis is oriented -45º North with respect to its true north axis (Fig. 4 and Fig. 5), eastern block is preferentially exposed to sunlight most part of the day. Thus, the intentional tilting of the DoA building must be the reason behind the preferential heating of the eastern block when compared to its western block. Ascribed hypothesis can be further understood and validated using the sun path diagram.

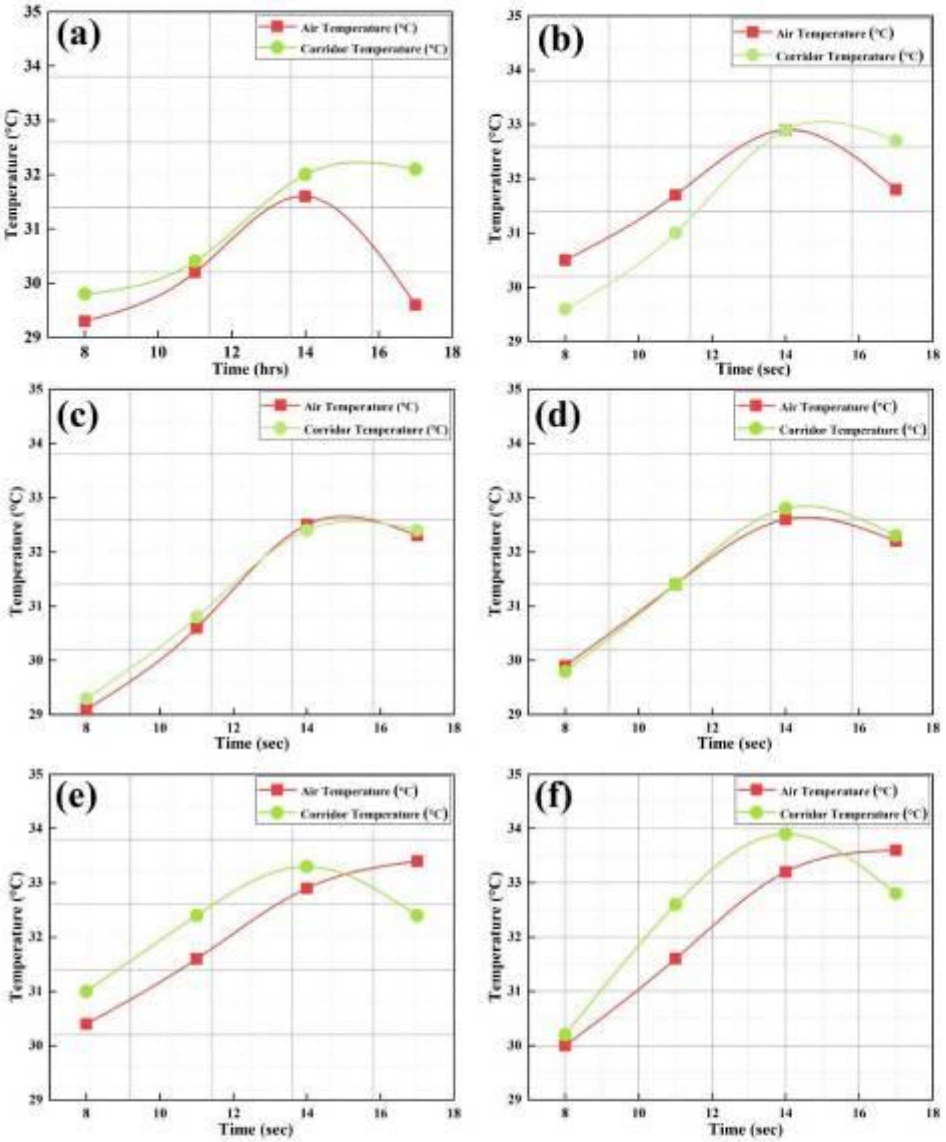

Fig. 7: Effect of building orientation on the room and corridor temperature distribution inside the classrooms (a) G2, (b) G4, (c) F1, (d) F0, (e) S1, and (f) S6

Table 3: The rate at which AT inside the room and corridor varies with time and floor levels
Source: Author

Room(s)	Position	Rate @ which AT increases	
		Room (°C/hr)	*Corridor (°C/hr)*
G2	West	0.503±0.048	0.579±0.067
G4	East	0.524±0.042	0.615±0.156
F1	West	0.411±0.038	0.564±0.006
F5	East	0.451±0.028	0.723±0.019
S1	West	0.416±0.009	0.517±0.047
S6	East	0.509±0.067	0.546±0.104

If the Fig. 2 is revisited there is no significant difference in the shadow area swept by the true North and -45° North oriented building. Moreover, it is evident from Fig. 2 that the -45° North oriented building exposes itself favorably to the sunlight, than its true North counterpart. For example, the luminescence corresponding to 8 am, 11 am, and 2 pm is apparently higher in the -45° North oriented building. This indicates that for a given set of experimental conditions, the -45° North oriented building heats up faster than its true North counterpart. To address this anomaly, the rate at which shadow area (of both courtyard and building) decreases in the true North and -45° North oriented building is calculated from Fig. 2. To our surprise, their magnitudes differ considerably as shown in Table 4. In case of the true North building, the shadow area (building/courtyard) decreases at a faster rate than its -45° North oriented counterpart. In other words, the -45° North oriented building is exposed to direct sunlight for extended periods of time, and this could probably be the reason behind the higher luminescence in the -45° North oriented building. Thus, the collective heating of the building surface, the courtyard, and the area surrounding the department could have increased the AT dynamics in the -45° oriented building. To validate this hypothesis, CFD simulations were done on the corridors and inside the classrooms, using IES-ve software.

Table 4: Rate at which building and courtyard shadow area varies from 8 am to 5 pm in the true North and -45° North oriented building
Source: Author

Building orientation	Rate @ which		
	Building shadow area decreases (m^2/hr)	Courtyard shadow area decreases (m^2/hr)	Courtyard exposed area increases (m^2/hr)
True North	9605±1234	2306±344	2215±395
-45° North	9849±1471	2340±262	2153±343

As the courtyard is coupled with the corridor and in turn with the classrooms, the exposure of the courtyard to sunlight can eventually perturb the air temperature dynamics inside the classrooms (refer to our earlier discussions from Fig. 2, Fig. 5, Fig. 8, and Table 4). Since the DoA building is oriented -45° to the true North, preferential heating of the classrooms is apparently higher. The images corresponding to the row 1, 2, and 3 in Fig. 9 indicates CT distribution contours in the ground, first, and the second level at 2.30 pm. The blue-colored regions in Fig. 9 indicate cooler regions, while the red-colored regions represent hotter regions. Column one and two in Fig. 9 helps one to compare/understand how the CT distribution varies in the western and eastern sides of the building. It is evident from Fig. 9 that the CT distribution is higher on the eastern side than its western counterpart. In case of the corridors located on the ground level, CT distribution is higher in G4, as shown in Fig. 9

(b). It should be noted that the CT is higher on the G4 corridor periphery and not in the middle. The probable reason behind the same would be the sun's position at 2.30 pm with respect to the G4 corridor space. According to the sun path diagram in Fig. 2, only a fraction of sunlight can be expected to interact with G4 corridor space, whereas most of the sunlight is interacting on F5 and S6. That is why the CT distribution contour of F5 is more reddish in color than G4 and S6. Moreover, the sun makes an obtuse angle (@ 2.30 pm) with G4 corridor space, which eventually increases the shadow area. When it comes to the CT distribution on the second level, one may expect a strong red-color contour for S6 than F5, but the CT trend is lower than G4. The probable reason behind the relatively cooler corridor temperature in S6 is its placement with respect to the true north. The sun path diagram corresponding to 2 pm in Fig. 2 indicates that the S6 corridor space is completely concealed from the direct sunlight, during most of part of the day. Finally, the IES-ve corridor simulations have helped us to visually understand the differential heating phenomenon (eastern side hotter than the western side) in the -45º North oriented building and how this orientation could perturb the AT in the classrooms.

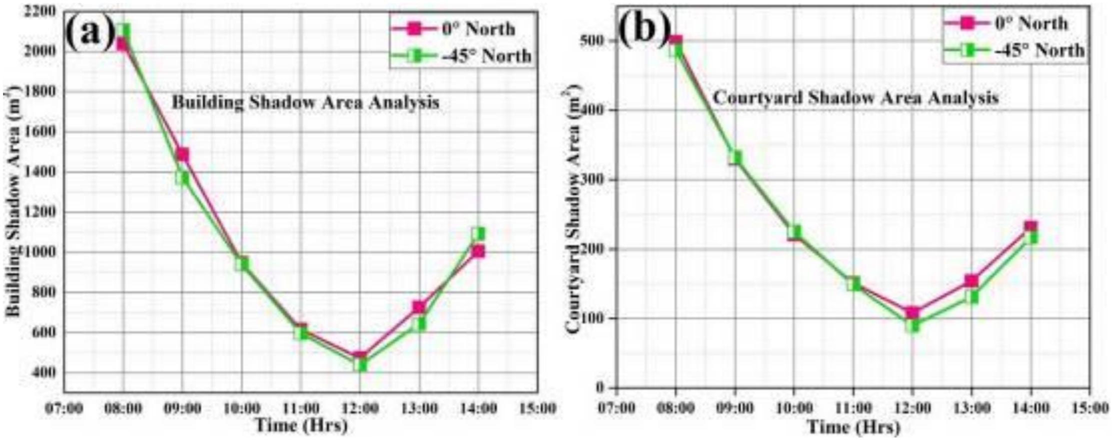

Fig. 8: Impact of building orientation on the (a) shadow area swept by the building and (b) shadow area swept by the courtyard

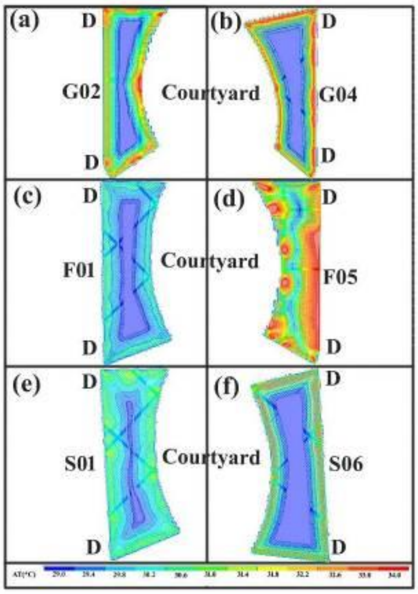

Fig. 9: Computational fluid dynamics simulation of AT in the corridor(s) positioned outside (a) G2, (b) G4, (c) F1, (d) F5, (e) S1, and (f) S6

Further, to visually comprehend the synergistic role of building orientation and corridor spaces on the AT dynamics inside the classrooms, CFD simulations were performed in the study area using IES-ve and the typical outcomes are presented in Fig. 10. Since all the arguments explained in context to Fig. 9 concedes with the outcomes presented in Fig. 10, the hypothesis explaining "can building orientation perturb the AT dynamics inside the classrooms?" is also true. It is evident from Fig. 10 that there is a considerable amount of hot air movement inside the classrooms via the windows and the doors. Now the question is, whether the corridor heating alone perturbs the AT dynamics inside the classrooms or is there any other parameter that contributes to rise in the classroom temperature? Irrespective of the levels, the classrooms in Fig. 10 clearly show red color contours near the windows and doors. Even if one gives full credit to the corridor spaces for circulating the hot air inside the classrooms near the doors, there is a considerable amount of hot air trying to enter the room via the window opening. Thus, the AT dynamics inside the classroom gets perturbed by the building orientation, corridor opening, and the window opening. Another fact that needs to be mentioned here is that, hot air prefers to enter the classrooms via the southern side of the building than the northern side. As the sun travels east to west via south during this period, the hot air progress via southern side of the of the building than its northern counterpart as shown in Fig. 2. And, that is the reason behind the red color contours around the window openings positioned along the southern side of the building. Among this the exception G02 which heats up intentionally in the northern side. This might be due to relatively larger window opening along the northern side, which could possibly favor hot air from the ground surface to progress via northern side.

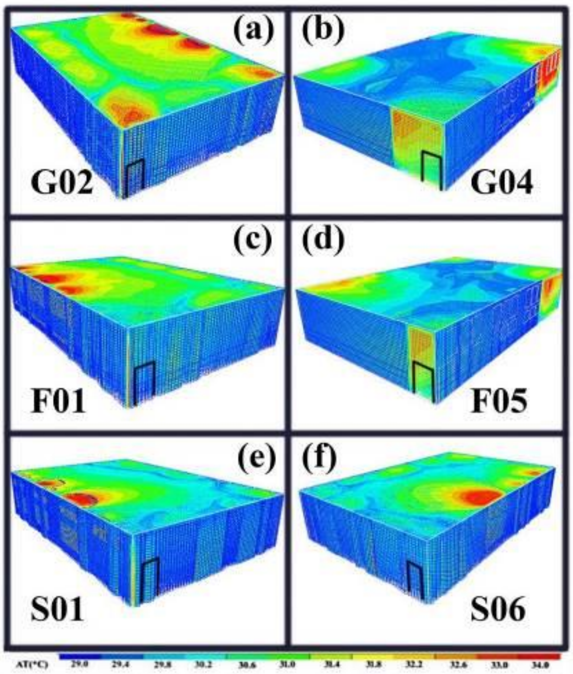

Fig. 10: Computational fluid dynamics simulation of AT of the rooms(s) rooms through IES-ve (a) G02, (b) G04, (c) F01, (d) F05, (e) S01 and (f) S06

The synergistic effect of the building orientation, the window opening, and the corridor spaces on the AT dynamics inside the classrooms were understood from the solar analysis as shown in the Fig. 11. The red color contour indicates a hotter surface while the blue colored region indicates a cooler surface. It is clear from Fig. 11 that sun-path, the window openings and its placement play a major role for hot air progress inside the classrooms. Since sun travels east to west via south during this period, the degree/rate of hot air movement inside the classrooms is apparently higher along the southern side of the building than its northern counterpart. Conversely, the degree of daylight progress inside the classrooms is relatively lower along the southern side than its northern counterpart. Thus, the solar analysis has provided us with enough clarity to understand, how the building orientation coupled with window parameters (placement and opening size) can perturb the day light progress/air flow rate inside the vernacular spaces.

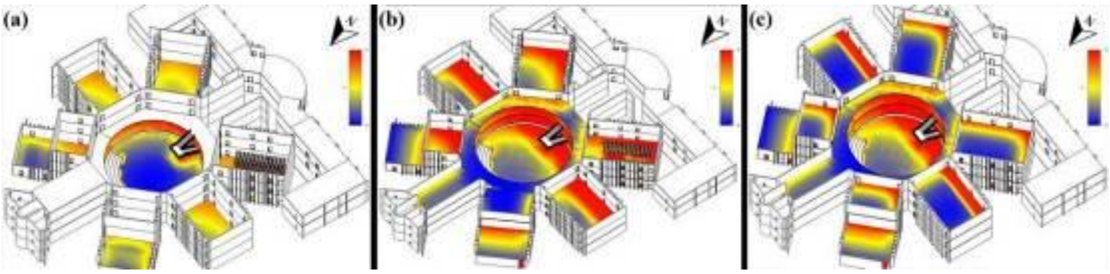

Fig. 11: Solar radiation analysis deciphering the coupled effect of the building orientation, the window placement, and window opening, on the AT dynamics in the (a) ground floor, (b) first floor, and (c) second floor

Discussion

Variation in the Air Temperature Observed from Field Experiments and CFD Simulations

In this section, we have compared the air temperature (AT) outcomes obtained from the field-experiments and CFD simulations, as shown in Fig. 12. The red and green color AT profile corresponds to the response from field-experiments and simulations, respectively. It is clear from Fig. 12 that the simulation profile goes in parallel with the experimental outcomes, with minor deviations here and there. Though the AT profiles of the simulation mimics the experimental data, their magnitudes differ marginally. Given the experimental/simulation conditions, the governing equation that best explains the room temperature dynamics inside the classroom(s) is found to be a third order polynomial or a cubic equation, as shown in Table 5. If one compares the data points (simulation and experimental) presented in Fig. 12 column-wise, it is evident that the AT distribution along the eastern side of the building is apparently higher than that of its western counterpart.

Table 5: Governing equation(s) that best describes the room temperature dynamics of a -45◦oriented building

Room No.	Governing equation			
	Room Temperature Experimental	**Ψ^2 (Exp.)**	**Room Temperature Simulation**	**Ψ^2 (Sim.)**
G2	$y = 58.41 - 8.66x + 0.81x^2 - 0.02x^3$	0.88	$y = 37.64 - 2.74x + 0.33x^2 - 0.01x^3$	0.89
G4	$y = 44.34 - 4.58x + 0.46x^2 - 0.01x^3$	0.86	$y = 42.46 - 3.67x + 0.38x^2 - 0.01x^3$	0.77
F1	$y = 45.61 - 5.33x + 0.53x^2 - 0.02x^3$	0.95	$y = 68.26 - 10.38x + 0.92x^2 - 0.03x^3$	0.88
F5	$y = 33.98 - 2x + 0.25x^2 - 0.007x^3$	0.91	$y = 92.46 - 17.26x + 1.56x^2 - 0.04x^3$	0.93
S1	$y = 34.19 - 1.66x + 0.19x^2 - 0.005x^3$	0.92	$y = 47.22 - 4.29x + 0.35x^2 - 0.008x^3$	0.94
S6	$y = 34.51 - 2.07x + 0.24x^2 - 0.007x^3$	0.95	$y = 46.54 - 5.44x + 0.57x^2 - 0.02x^3$	0.93

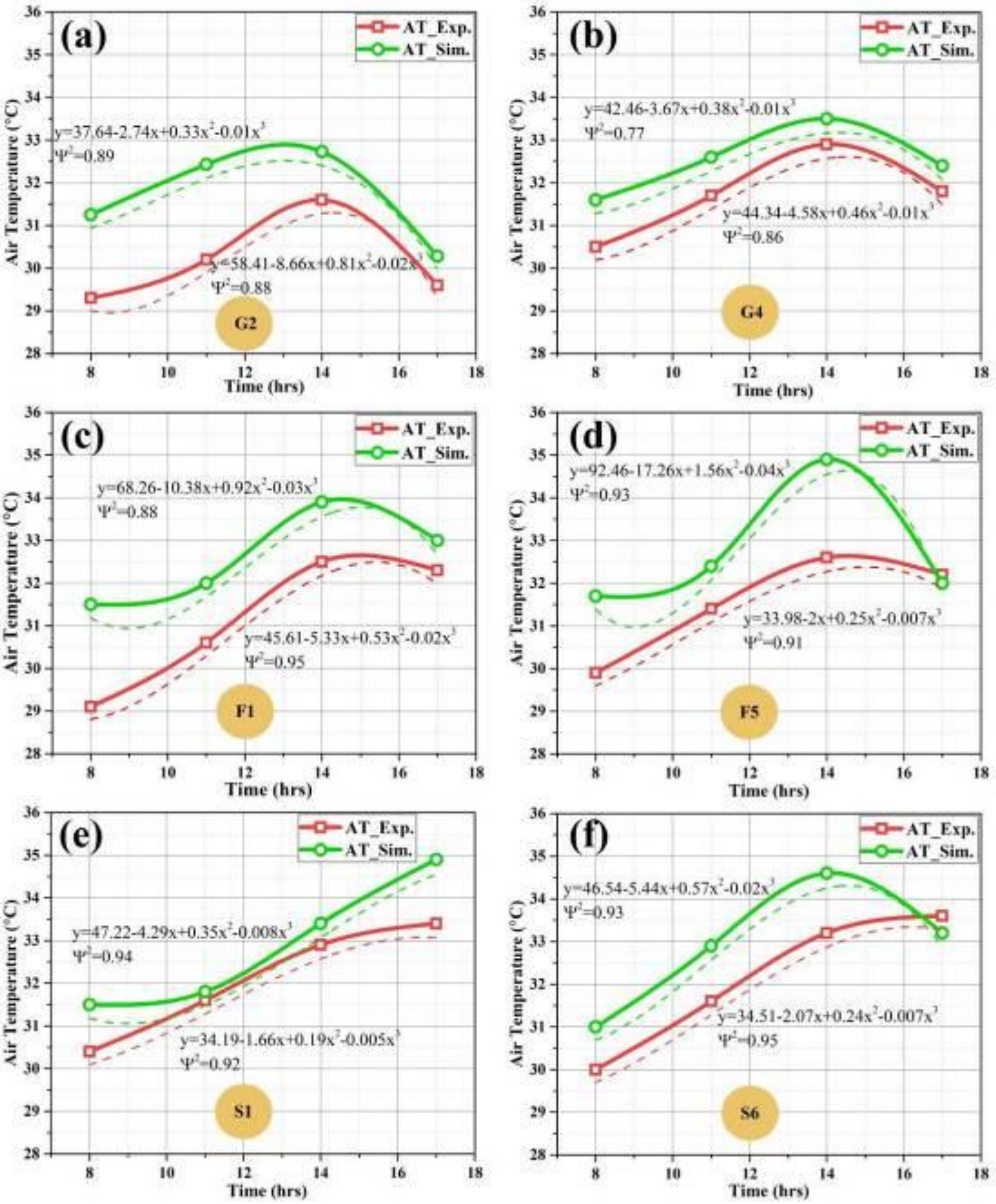

Fig. 12: Disparities observed in the room temperature dynamics acquired from field experiments and CFD simulations

Variation in the Corridor Temperature Observed from Field Experiments and CFD Simulations

In this section, we have compared the corridor temperature (CT) outcomes obtained from the field experiments and CFD simulations using Fig. 13. Both, the experimental and simulation profiles follow a similar trend, with minor deviations here and there, as shown in Fig. 13. But, when it comes to the magnitude of the corridor temperatures, the experimental and simulation outcomes differ slightly, similar to what we have observed earlier with air temperature distributions (see Fig. 12). The possible reason(s) behind the deviation needs to be understood and will be of utmost priority in our future work. The rationale behind the corridor temperature distribution in a -45º North oriented building is best illustrated by the governing equations presented in Table 6. By comparing the experimental and simulation outcomes based on the Fig. 12 and Fig. 13, following inferences were deduced; (a) eastern side of the building is hotter than its western counterpart, (b) southern side of the building heats up faster than its northern counterpart, (c) preferential building orientation (-45º North) introduces a differential heating phenomenon leading to extensive heating of eastern corridors/rooms when compared to their western counterpart, (d) F5 corridor space heats up faster than other corridor spaces, and (e) it also proves that the maximum amount of solar radiation enters through the windows than the corridor spaces and door opening.

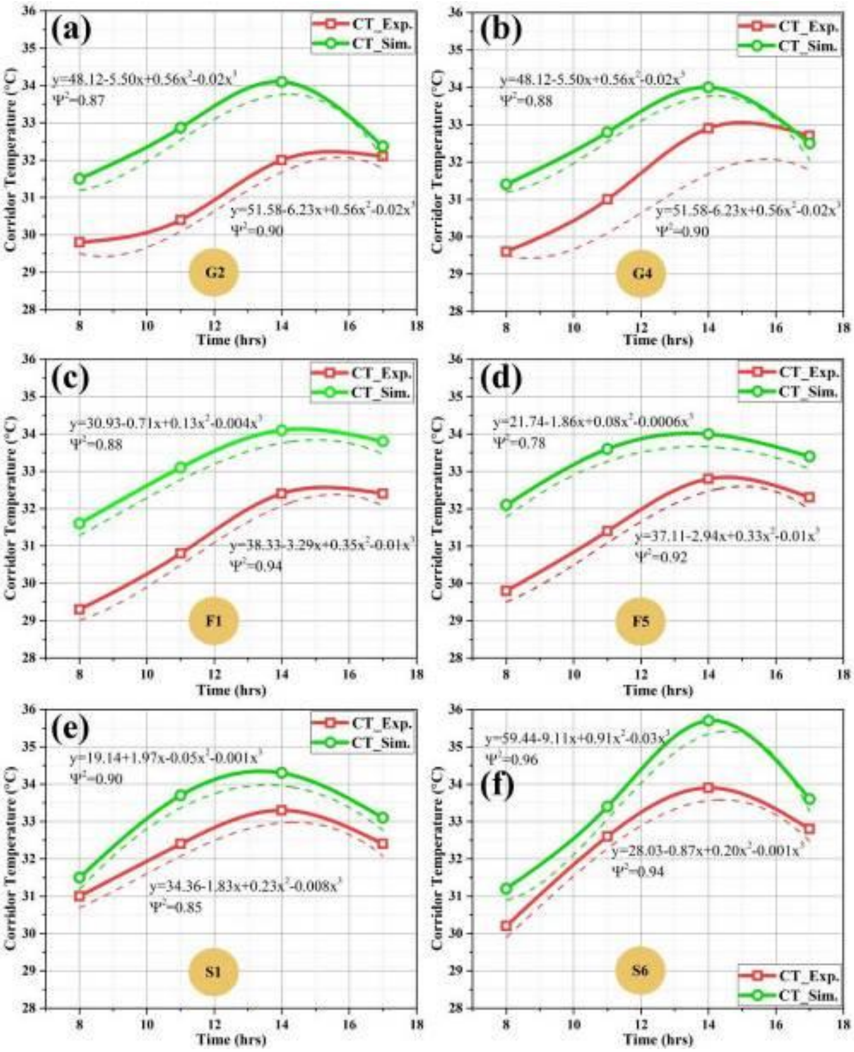

Fig. 13: Disparities observed in the corridor temperature dynamics acquired from field experiments and CFD simulations

Table 6: Governing equation(s) that best describes the corridor temperature dynamics of a -45º oriented building

Room No.	Governing Equation			
	Corridor Temperature Experimental	Ψ2 (Exp.)	Corridor Temperature Simulation	Ψ2 (Sim.)
G2	$y = 51.58 - 6.23x + 0.56x^2 - 0.02x^3$	0.90	$y = 48.12 - 5.50x + 0.56x^2 - 0.02x^3$	0.87
G4	$y = 51.58 - 6.23x + 0.56x^2 - 0.02x^3$	0.90	$y = 48.12 - 5.50x + 0.56x^2 - 0.02x^3$	0.88
F1	$y = 38.33 - 3.29x + 0.35x^2 - 0.01x^3$	0.94	$y = 30.93 - 0.71x + 0.13x^2 - 0.004x^3$	0.88
F5	$y = 37.11 - 2.94x + 0.33x^2 - 0.01x^3$	0.92	$y = 21.74 - 1.86x + 0.08x^2 - 0.0006x^3$	0.78
S1	$y = 34.36 - 1.83x + 0.23x^2 - 0.008x^3$	0.85	$y = 19.14 + 1.97x - 0.05x^2 - 0.001x^3$	0.90
S6	$y = 28.03 - 0.87x + 0.20x^2 - 0.001x^3$	0.94	$y = 59.44 - 9.11x + 0.91x^2 - 0.03x^3$	0.96

Conclusions

This paper examined the role of building orientation on the shadow behavior, corridor temperature, room temperature dynamics, and the degree of daylight progress inside a vernacular building using field experiments and computational fluid dynamic simulations. The building/courtyard shadow area fades away faster in the -45º North oriented building. The -45º North oriented building exposes itself favorably to the sunlight than its true North counterpart. This phenomenon exposes the East face of the building to direct sunlight, for the most part of the day. This eventually leads to the preferential heating of the eastern side over its western counterpart (G4, F5, and S6). This hypothesis was validated with building simulations using IES-ve and Autodesk Revit Insight. Building simulation outcomes concede with the experimental results, with minor deviations. Building simulation and solar analysis outcome leads us to the following inferences;

(i) The study area has been preferentially oriented to -45º (w.r.t true north axis) to harness the potential benefits of the vernacularism.
(ii) The building orientation plays a crucial role in deciphering the air temperature dynamics inside the vernacular spaces located in southern India.
(iii) The AT dynamics inside the classrooms is perturbed by the hot air entering through the window opening positioned along the southern side of the building.
(iv) The northern side of the classrooms are relatively cooler than its southern counterpart.
(v) The solar radiation analysis confirms that the eastern side of the building heats up faster rate than its western counterpart.
(vi) The daylight progress is relatively higher inside the classrooms located in the northern side than its southern counterpart
(vii) The building orientation solely decides the degree of differential heating phenomenon inside the classrooms.
(viii) The mathematical models may be used to predict the air/corridor temperature dynamics inside the vernacular spaces located in warm-humid climatic conditions.

References

Albabely, S. and Alobaydi, D. (2023) ‘Impact of Urban Form on Movement Densities: The Case of Street Networks in AlKarkh, Baghdad, Iraq’, *ISVS e-journal*, 10(7), pp. 147–163.

Ali, M. H., Asmal, I. and Amin, S. (2023) ‘The Influence of Livelihoods on Coastal Settlement Patterns in Kampung Padang’, *IOP Conference Series: Earth and Environmental Science*, 1272(1), pp. 012039. doi: 10.1088/1755-1315/1272/1/012039.

Al-Kodmany, K. (2017). Building orientation and form in vernacular architecture: Lessons from the Middle East. Frontiers of Architectural Research, 6(2), 254-264.

Allouhi, A. *et al.* (2015) ‘Energy consumption and efficiency in buildings: Current status and future trends’, *Journal of Cleaner Production*. Elsevier Ltd, 109, pp. 118–130. doi: 10.1016/j.jclepro.2015.05.139.

Alonso, L. and Renard, F. (2020) ‘A new approach for understanding urban microclimate by integrating complementary predictors at different scales in regression and machine learning models’, *Remote Sensing*, 12(15). doi: 10.3390/RS12152434.

Aydin, E., Correa, S. B. and Brounen, D. (2019) ‘Energy performance certification and time on the market’, *Journal of Environmental Economics and Management*. Elsevier Inc., 98, p. 102270. doi: 10.1016/j.jeem.2019.102270.

Banerjee, R., & Koenigsberger, O. (1980). Environmental design considerations in low-cost housing for developing countries. Building and Environment, 15(1), pp. 25-35.

Bilgen, S. (2014) ‘Structure and environmental impact of global energy consumption’, *Renewable and Sustainable Energy Reviews*. Elsevier, 38, pp. 890–902. doi: 10.1016/j.rser.2014.07.004.

Binici, H. (2007) ‘March 12 and June 6, 2005 Bingol-Karliova earthquakes and the damages caused by the material quality and low workmanship in the recent earthquakes’, *Engineering Failure Analysis*, 14(1), pp. 233–238. doi: 10.1016/j.engfailanal.2005.10.020.

Blengini, G. A. (2009) ‘Life cycle of buildings, demolition and recycling potential: A case study in Turin, Italy’, *Building and Environment*, 44(2), pp. 319–330. doi: 10.1016/j.buildenv.2008.03.007.

Dascalaki, E. G. *et al.* (2013) ‘Energy certification of Hellenic buildings: First findings’, *Energy and Buildings*. Elsevier B.V., 65, pp. 429–437. doi: 10.1016/j.enbuild.2013.06.025.

Dear, M., & Flusty, S. (1998). Postmodern urbanism. Annals of the Association of American Geographers, 88(1), pp. 50-72.

Dimoudi, A. *et al.* (2013) ‘Investigation of urban microclimate parameters in an urban center’, *Energy and Buildings*. Elsevier B.V., 64, pp. 1–9. doi: 10.1016/j.enbuild.2013.04.014.

Diz-Mellado, E. *et al.* (2021) ‘Applied machine learning algorithms for courtyards thermal patterns accurate prediction’, *Mathematics*, 9(10), pp. 1–19. doi: 10.3390/math9101142.

Doctor-Pingel, M. *et al.* (2019) ‘A study of indoor thermal parameters for naturally ventilated occupied buildings in the warm-humid climate of southern India’, *Building and Environment*. Elsevier, 151(January), pp. 1–14. doi: 10.1016/j.buildenv.2019.01.026.

Fan, Y. and Xia, X. (2018) ‘Energy-efficiency building retrofit planning for green building compliance’, *Building and Environment*. Elsevier Ltd, 136, pp. 312–321. doi: 10.1016/j.buildenv.2018.03.044.

Fathy, H. (2000). Architecture for the poor: An experiment in rural Egypt. University of Chicago Press.

Fawzi Al-Nuaimi, S. and Maki Mohammed, W. (2022) ‘Creating Preventive Spaces: A strategy for designing environmental urban spaces to deter the pandemics’, *ISVS e-journal*, 9(3), pp. 201–220.

Gul, M. S. and Patidar, S. (2015) ‘Understanding the energy consumption and occupancy of a multi-purpose academic building’, *Energy and Buildings*. Elsevier B.V., 87, pp. 155–165. doi: 10.1016/j.enbuild.2014.11.027.

Gulyás, Á., Unger, J. and Matzarakis, A. (2006) ‘Assessment of the microclimatic and human comfort conditions in a complex urban environment: Modelling and measurements’, *Building and Environment*, 41(12), pp. 1713–1722. doi: 10.1016/j.buildenv.2005.07.001.

Hassan, A. (1981). Vernacular Architecture in the Arabian Peninsula: The Red Sea Coast of Saudi Arabia. British Archaeological Reports.

Herrando, M. *et al.* (2016) ‘Energy Performance Certification of Faculty Buildings in Spain: The gap between estimated and real energy consumption’, *Energy Conversion and Management*, 125(January 2014), pp. 141–153. doi: 10.1016/j.enconman.2016.04.037.

Ishrat, A. *et al.* (2023) ‘Climate and Seismic Responsive Vernacular Architecture of the Old Settlement of Srinagar, India’, *ISVS e-journal*, 10(7), pp. 106–121.

Ivkovska, V. (2020) ‘The Ottoman Era Town House in Ohrid, Macedonia: An analysis of typology and construction’, *ISVS e-journal*, 7(3), pp. 49–59.

Iwaro, J. and Mwasha, A. (2010) ‘A review of building energy regulation and policy for energy conservation in developing countries’, *Energy Policy*. Elsevier, 38(12), pp. 7744–7755. doi: 10.1016/j.enpol.2010.08.027.

Jonkutė, G. *et al.* (2021) ‘Analysis of carbon dioxide emissions in residential buildings through energy performance certification in Lithuania’, *Energy Sources, Part B: Economics, Planning and Policy*. Taylor & Francis, 16(2), pp. 198–215. doi: 10.1080/15567249.2020.1773581.

Kabir, G., Sadiq, R. and Tesfamariam, S. (2014) ‘A review of multi-criteria decision-making methods for infrastructure management’, *Structure and Infrastructure Engineering*, 10(9), pp. 1176–1210. doi: 10.1080/15732479.2013.795978.

Kaplan, S. (1995). The restorative benefits of nature: Toward an integrative framework. Journal of Environmental Psychology, 15(3), pp. 169-182.

Kariminia, S. *et al.* (2016) ‘A systematic extreme learning machine approach to analyze visitors’ thermal comfort at a public urban space’, *Renewable and Sustainable Energy*

Reviews, 58, pp. 751–760. doi: 10.1016/j.rser.2015.12.321.

Kordhaghi, M., Zolfaghari, H. and İnceoglu, M. (2022) ‘Climatic Sensitivity and Architecture of Traditional Houses in Iran during the Qajar Dynasty (1795-1925)’, *ISVS e-journal*, 9(3), pp. 1–21.

Koushki, P. A. and Kartam, N. (2004) ‘Impact of construction materials on project time and cost in Kuwait’, *Engineering, Construction and Architectural Management*, 11(2), pp. 126–132. doi: 10.1108/09699980410527867.

Li, Y. *et al.* (2019) ‘Review of building energy performance certification schemes towards future improvement’, *Renewable and Sustainable Energy Reviews*, 113(February). doi: 10.1016/j.rser.2019.109244.

Low, S. M. (2003). Behind the gates: Life, security, and the pursuit of happiness in fortress America. London: Routledge.

Marzouk, M. M., El Kherbawy, A. A. & Khalifa, M. (2013) ‘Factors influencing sub-contractors selection in construction projects’, *HBRC Journal*. Housing and Building National Research Center, 9(2), pp. 150–158. doi: 10.1016/j.hbrcj.2013.05.001.

Mehta, V. & Pal, S. (2018). Vernacular Architecture and Environmental Sustainability: A Critical Perspective. International Journal of Sustainable Built Environment, 7(1), 36-47.

Monga, C. & Das, A. K. (2018) ‘A comparative visual study of design elements of social cultural institutions, “Namghar” with monuments in South East Asia’, *ISVS e-journal*, 5(2), pp. 31–41.

Moughtin, C., Suman, B. & Shirley, P. (1999). Urban Design: Street and Square (3rd ed.). London: Architectural Press.

Nasar, J. L. & Terzano, K. (2010). The Sacred and the Profane in Islamic Architecture: A Room of One's Own? Journal of Urban Design, 15(1), pp. 1-17.

Olgyay, V., & Olgyay, A. (1963). Design with climate: Bioclimatic approach to architectural regionalism. New York: Princeton University Press.

Oliver, P. (1989). Dwellings: The Vernacular House World Wide. Phaidon Press.

Ozbek, M. (2018). Vernacular architecture: An investigation into the effects of building orientation on thermal comfort in traditional Turkish houses. Building and Environment, 145, pp.153-166.

Parkinson, A. *et al.* (2013) ‘Energy performance certification as a signal of workplace quality’, *Energy Policy*. Elsevier, 62, pp. 1493–1505. doi: 10.1016/j.enpol.2013.07.043.

Pérez-Lombard, L., Ortiz, J. and Pout, C. (2008) ‘A review on buildings energy consumption information’, *Energy and Buildings*, 40(3), pp. 394–398. doi: 10.1016/j.enbuild.2007.03.007.

Qiu, Y. and Kahn, M. E. (2019) ‘Impact of voluntary green certification on building energy performance’, *Energy Economics*. Elsevier B.V., 80, pp. 461–475. doi: 10.1016/j.eneco.2019.01.035.

Rapoport, A. (1969). House Form and Culture. New York: Prentice-Hall.

Rawal, R. *et al.* (2016) ‘Clothing insulation as a behavioural adaptation for thermal comfort in Indian office buildings’, *Proceedings - 9th International Windsor Conference 2016: Making Comfort Relevant*, (August), pp. 403–415.

Salazar Trujillo, J. H. (1998) ‘Solar Performance and Shadow Behaviour in Buildings. Case Study with Computer Modelling of a Building in Loranca, Spain’, *Building and Environment*, 33(2–3), pp. 117–130. doi: 10.1016/s0360-1323(97)00027-9.

Santamouris, M., et al. (2018). Review of heat transfer phenomena on building envelopes. Part 1: Heat transfer coefficients. Renewable and Sustainable Energy Reviews, 82, pp. 1337-1358.

Saraswat, A., Pipralia, S. and Kumar, A. (2024) ‘Rapid Transformations of Vernacular settlements to Urban Areas around Metropolitan Cities in India : A Review’, 11(01), pp. 24–42.

Soewarno, N. (2014) ‘Transformations of Vernacular Buildings: Chinatown in Bandung City, Indonesia’, *ISVS e-journal*, 3(1), pp. 42–49.

Tombesi, P. (2006) ‘Good thinking and poor value: On the socialization of knowledge in construction’, *Building Research and Information*, 34(3), pp. 272–286. doi: 10.1080/09613210600634336.

Village, N. (2019) ‘Sustainable Transformation of a Vernacular Habitat through the Revival of Crafts ’:, *ISVS E-journal*, 6(4), pp. 1–16.

Wekesa, B. W., Steyn, G. S. & Otieno, F. A. O. (2010) ‘The response of common building construction technologies to the urban poor and their environment’, *Building and Environment*. Elsevier Ltd, 45(10), pp. 2327–2335. doi: 10.1016/j.buildenv.2010.04.019.

Wong, N. H., Jusuf, S. K. & Tan, C. L. (2011) ‘Integrated urban microclimate assessment method as a sustainable urban development and urban design tool’, *Landscape and Urban Planning*. Elsevier B.V., 100(4), pp. 386–389. doi: 10.1016/j.landurbplan.2011.02.012.

Yassin, M. M., et al. (2020). Vernacular building orientation and design strategies in hot arid climates: A case study of traditional courtyard houses in Yemen. Sustainability, 12(8), pp. 3178.

Zhang, Y. P. *et al.* (2006) ‘Preparation, thermal performance and application of shape-stabilized PCM in energy efficient buildings’, *Energy and Buildings*, 38(10), pp. 1262–1269. doi: 10.1016/j.enbuild.2006.02.009.

Zhou, Z. *et al.* (2016) ‘Achieving energy efficient buildings via retrofitting of existing buildings: A case study’, *Journal of Cleaner Production*, 112, pp. 3605–3615. doi: 10.1016/j.jclepro.2015.09.046.