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Smart Vernacular Architecture: A Framework for Assessment and Virtual Reality-based Visualisation of Indigenous Toda Dwellings

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Abstract

Indigenous communities and their way of life are facing significant challenges due to globalisation, industrialisation and urbanisation, which have forced them to gradually adopt the architecture, lifestyle, and culture of mainstream society. This paper proposes a Smart Vernacular Architecture (SVA) framework and applies it to the indigenous dwellings of the Todas, a tribal community living in India's Nilgiri mountains. The architecture and indoor space quality of these dwellings are investigated in this paper based on specific thermal comfort parameters like the interior temperature and airflow. The indoor temperatures of Toda dwellings are simulated for the predicted climate of 2100 to evaluate their climate resilience. Finally, the paper illustrates the usage of virtual reality (VR) to explore and visualise the Toda settlement and the interior environment parameters of a Toda dwelling to effectively convey and preserve the knowledge of vernacular architecture. In a nutshell, this paper elucidates the advantages of vernacular architecture and construction methods to arouse the interest of academics, policymakers, students, and professionals in preserving architecture, culture, and indigenous knowledge.

Keywords: Smart Vernacular; Virtual Reality; Visualisation; Toda hut; Architecture; Thermal performance; Climate Resilience

1. Introduction

This paper leverages immersive technologies like Extended Reality (XR)—including Virtual Reality and Mixed Reality—and their expanding use in the fields of Architecture, Engineering and Construction (AEC), and education.

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Virtual Reality (VR) allows a user to immerse in a computer-generated virtual world while completely shutting off the real world. Hence, a VR user can interact with and navigate an imaginary world (completely different from the real world), a virtual world inspired by reality, or a real world that has been modified or enhanced with the addition of specific entities (e.g., information overlays on objects, and so on). This study uses virtual reality to examine the architecture of Toda huts—a well-known tribal group living in India's Nilgiri mountains—and visualises the indoor air parameters in these dwellings. In this study, virtual reality (VR) serves two purposes: (a) to help educate academicians, architects, students, and the general public about the Toda huts' architecture, which is hitherto invisible to mainstream society; and (b) to help researchers and enthusiasts visualise the Toda huts' current and predicted thermal comfort to emphasise the sustainability of such indigenous architecture.

1.1. The Indigenous community, vernacular architecture, and present-day challenges

Indigenous communities are strongly rooted in their unique vernacular language, culture, and customs which are distinct and, to a large extent, not influenced by the institutions and culture of the mainstream societies. Indigenous or tribal communities are often localised to a particular geographical context and governed by their distinct socioeconomic customs. Todas are an ethnic pastoral community residing in the Nilgiri ranges (Fig. 1.) along with the Kotas, Badagas, Kurumbas and Irulas. Trade in buffalo milk, butter, and hides, as well as traditional embroidery work, are typical activities for the Todas [1]. The grassy meadows of the Nilgiri Hills are home to Toda villages, where small woods surround the larger plateau [1]. The Todas inhabit barrel-vault-shaped huts with thatched roofs made of dried grass (Fig. 1.). The roofs are built using a base framework of longitudinal wooden members, bent cane bamboos, and split bamboos [2]. The front and back walls have small openings for doors and windows and are made of either granite stones or wooden panels plastered with mud and dung [2].

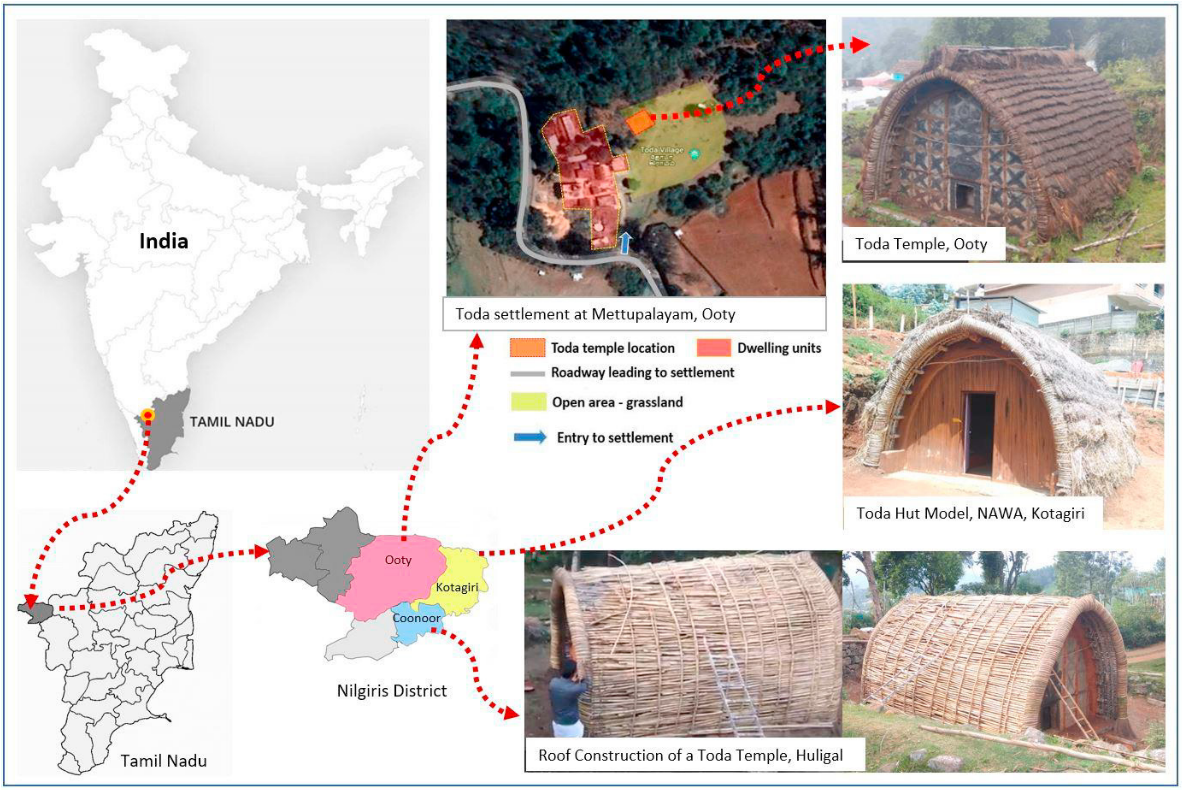

Fig. 1. Geographical context of the Todas and their architecture

Due to the increasing influence of globalisation, industrialisation, and urbanisation, the Toda community is rapidly transitioning to brick and mortar-based dwellings with the assistance of government bodies. Indigenous architecture and construction may face extinction over the coming generations due to the increased adoption of conventional construction methods exhibiting superior structural performance and durability. Hence, this paper tries to investigate the advantages of Toda architecture using objective tools and devise a practical framework for preserving the intuitive knowledge of vernacular architecture.

1.2. Literature Review

Vernacular architecture refers to built forms that are not part of the mainstream of professional architecture [3]. Examples include low-energy and low-resource structures like thatched cottages, Igloos, bamboo dwellings, mud huts, etc. In other words, vernacular architecture refers to buildings created by people whose design choices are influenced by environmental and cultural considerations [4]. Many studies have evaluated the performance of vernacular architecture, as demonstrated by employing building energy modelling for various vernacular building characteristics from different climate regions [4], exploring the thermal comfort of the vernacular architecture of the ancient city of Pompeii using computer simulations [5], and using Computational fluid dynamics (CFD) for simulating convective heat transfer in Japanese vernacular architecture [6]. However, not many studies have been done to analyse the performance of vernacular built forms in the light of climate change scenarios. A study by Henna et al. (2021) investigates the climate resilience of Indian vernacular and conventional dwellings located in three distinct climate zones—namely temperate, warm-humid, and cold climate zones—for the years 2030, 2040, and 2050 based on A1B, A2 and B1 climate change scenarios [7]. The study indicated that vernacular dwellings, in general, performed better than conventional dwellings in terms of maintaining indoor temperatures for future climate scenarios [7]. Literature based on the effect of climate change is also present, for instance, to predict the district heat demand using a stochastic dynamic building stock model [8] or to investigate the energy demand and overall energy performance for residential buildings in Italy for the near term and long-term periods using dynamic simulation [9]. On the other hand, this paper seeks to assess the vernacular architecture of the Todas—more precisely, their indigenous dwellings—for resilience to climate change and thermal comfort.

1.3. Aim of the paper

This paper aims to assess the climate resilience of the traditional architecture of the Todas and study the indoor environment conditions of a Toda dwelling made from non-conventional materials. This paper also disseminates information on the indoor parameters and spatial characteristics of indigenous dwellings in an interactive and immersive way using virtual reality. To accomplish this goal, the following objectives were formulated:

- The paper first proposes a Smart Vernacular Architecture (SVA) framework to objectively evaluate any vernacular built form with the help of technology to gather, interpret, and represent data from such buildings.
- Secondly, the paper aims to test the SVA framework for Toda dwellings and assess the Toda Hut's thermal comfort by simulating the hut's indoor air temperature and airflow based on the external atmospheric conditions. In addition to 2020, simulations of the hut's interior temperatures are also run for a hypothetical future year (2100), which takes into account how the hut's inhabitants will be affected by the effects of global climate change. The thermal analysis has been conducted on a Computer Aided Design (CAD) model of a generic Toda hut to analyse the variation in internal air temperature against specific values of external air temperature. The external air temperature values correspond to the generated dry bulb temperature of the hottest day, coldest day, and the day with a high-temperature range, for the years 2020 and 2100, at Ooty. In order to compare the thermal comfort offered by indigenous versus conventional architectures, a hollow cube made of brickwork and concrete that represents the same volume as a traditional Toda hut has been subjected to thermal analysis under the same external conditions. In addition, CFD (computational fluid dynamics) tools are used to simulate air velocity—another factor affecting thermal comfort—at a point inside the Toda hut.
- Thirdly, the paper aims to formulate a VR model of the Toda hut, which allows the viewers to visualise the indoor parameters—like the indoor temperature and air velocity of the Toda hut—by interacting with an interactive dashboard, which builds upon the data generated from the aforementioned thermal simulations.

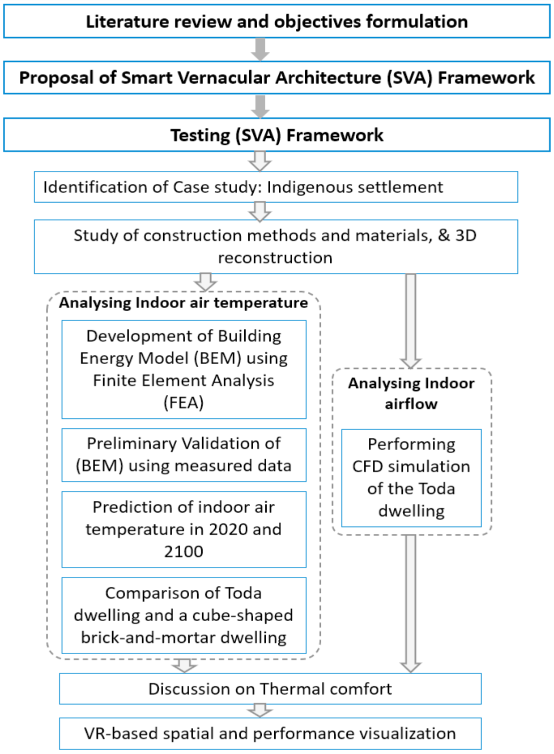

Fig. 2. Overview of the Methodology adopted in the paper

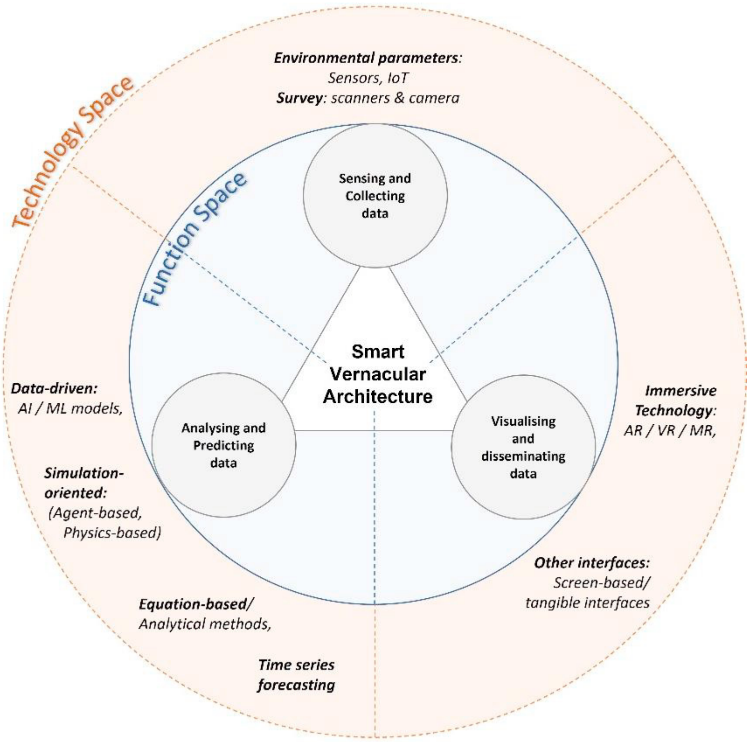

Fig. 3. A schematic representation of Smart Vernacular Architecture Framework

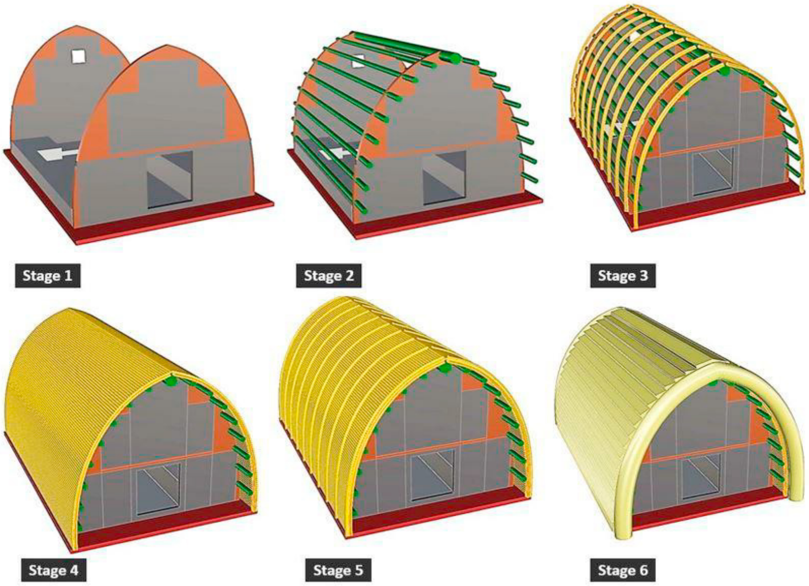

Fig. 4. CAD 3D model showing the stages of construction of a representative Toda temple or a dwelling.

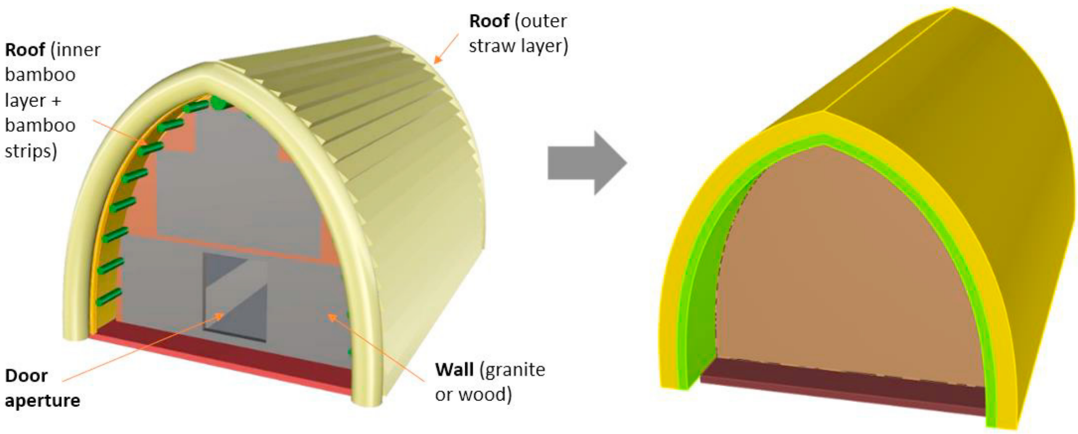

Fig. 5. Detailed and simplified CAD model of Toda hut

2. Methodology

Fig. 2 elucidates the methodology adopted in the paper for developing the smart vernacular architecture (SVA) framework and testing the same on an indigenous settlement of the Toda community. Testing the SVA framework entails identifying the context (i.e., the indigenous Toda settlements), looking at construction methods, reconstructing the vernacular dwellings in 3-D, evaluating the indoor environment parameters (air temperature and airflow), and visualising the spatial and performance aspects of Toda huts in VR. The key components described in this section are:—1) SVA framework and its testing, 2) thermal analysis for simulating the indoor air temperatures of a Toda hut vis-a-vis a brick-and-mortar cubical dwelling, 3) CFD analysis of the Toda hut for simulating indoor airflow, and 4) VR application design for visualising indoor environment parameters and architecture of Toda huts. The following subsections describe the specific objectives associated with each element of the thermal analysis, CFD analysis, and VR-based visualisation. For instance, the thermal analysis methodology engenders— a) creating 3D CAD models of a Toda hut and a brickwork cube geometry, b) obtaining building material information for both geometries, c) determining the exterior temperature for 2020 and 2100 using generated weather data, d) choosing a heat transfer method, and e) defining the analysis boundary conditions, parameters, and assumptions. The Computational fluid dynamics (CFD) methodology for simulating the air movement inside the Toda hut involves the creation of a unified air volume—comprising the hut's indoor and immediate outdoor air volumes—along with specifying the boundary conditions and settings for the analysis. The methodology for VR application design involves the design of a virtual environment, navigation, and interactions with a dashboard for visualising the environmental parameters of a Toda hut.

2.1. Smart Vernacular architecture and its application to Toda architecture

This paper develops a framework for the Smart Vernacular Architecture (SVA), which focuses on a technology-driven approach to studying and monitoring a vernacular built form. The SVA framework comprises three main functions: — 1) sensing and collecting data from the vernacular built forms, 2) analysing and predicting data related to the vernacular built forms, and 3) visualising and disseminating the vernacular built form data to the public and relevant stakeholders (Fig. 3.). The SVA framework can be applied to the architectural entity of a particular indigenous or local community in a specific geographical context. Each function in the SVA framework can be implemented by specific technologies comprising hardware, software, and integration between the two. For example, the function of sensing and collecting data on a vernacular architectural entity would be achieved by employing sensors—base sensors or IoT-based smart sensors—to record both indoor and outdoor environmental parameters and surveying tools like scanners and cameras. The collected data—numbers, images or videos—may be static or spatiotemporal. The technology adopted for analysing and predicting data collected from vernacular built forms revolve largely around various types of algorithms. Machine learning (ML)—a prominent type of AI algorithm—functions on a considerable amount of data of the built forms for classification, forecasting, and predictions. Furthermore, simulation-oriented analysis, which can take many forms, from agent-based to physics-based modelling, can help predict parameters for hypothetical future scenarios in addition to offering insights into the current functional or formal aspects of vernacular architecture. The function of visualising and disseminating data related to vernacular built forms from the earlier function stages would involve the adoption of various human-computer interfaces—comprising virtual and mixed realities and other interfaces like screen-based or tangible interfaces—all employing data and geometry visualisation techniques. The SVA framework effectively integrates appropriate technologies across the three functions in terms of their identification, usage and association by addressing the following questions: — 1) 'what specific vernacular built form is in consideration?', 2) 'what key aspect(s) of the vernacular architecture needs to be studied and why?', and 3) 'How would the identified aspects be studied?'.

Testing of the SVA framework is demonstrated in this paper by focusing on the dwellings of the Todas, which are semi-barrel-shaped huts made from locally sourced materials like bamboo, cane, wood, dried grass, granite, soil, and dung, situated in the Nilgiris. The aspects of indoor air temperature and airflow influencing the thermal comfort inside a Toda hut are considered for the study. One of the primary reasons for this analysis involves the increasing shift of the Todas from their traditional dwellings to the brick-masonry-based dwellings and their emerging adaptability to modern homes, which can potentially deplete the knowledge of traditional construction methods in future generations. Also, the study investigates specific parameters affecting the thermal comfort provided by an indigenous dwelling made from locally sourced materials compared to the present-day brick-and-mortar dwelling unit; and comments on the suitability of these indigenous dwellings to climate change. The sensing and data collection involves obtaining the survey and dimensional data of the Toda huts (to build a 3-D CAD model of a Toda hut) and the weather data of the geographical context (i.e., Ooty, in Tamil Nadu, India). The analysis and prediction stage involves physics-based simulations for air temperature and air velocity inside a Toda hut based on external weather conditions. The data visualisation and dissemination stage employs virtual reality (VR) to explore and view the spatial and performance data of the Toda dwellings.

2.2. Thermal analysis methodology

Following are the steps adopted for performing transient thermal analysis using Ansys software for the traditional Toda hut geometry and a hollow cube—in brickwork and concrete—of equivalent volumes.

2.2.1. Preparation of the 3-D model for the Toda hut

Based on the field observations, photographic documentation and dimensional study of the model Toda huts—one at NAWA, Kotagiri, and the other at Tribal Research Centre (TRC), Ooty—a detailed 3-D CAD model of a generic Toda hut is prepared, with the interior volume measuring approximately 4.75 metres in length, 3.18 metres in width and 2.8 metres in height. The detailed 3-D CAD model represents six distinct construction stages for Toda huts (and temples): — a) preparing the ground and laying stone for lateral walls; b) positioning primary longitudinal wooden members over the lateral walls to serve as a skeletal framework for the roof; c) tying and bending cane bamboos over the primary longitudinal wooden members and placing members roughly at an interval of 0.6 metres; d) horizontal positioning of split bamboos and tying them with the bent members; e) placing additional cane members at the top of the horizontal split bamboos which are tied to the underlying bent members with bamboo fibres; f) thatching process with grass (Fig. 4.). The lateral walls of residential huts were traditionally made of wood, but over time, stone slabs were also utilised, a practise now more commonly evident in Toda temples. The assembly of the dwelling unit is carried out internally within the community, where members work together in a synergistic way to build the timber, bamboo, and thatch-based huts. In comparison, complex procedures like carving out an aperture void from granite would require outsourcing the work to specific external communities when using stone as a construction material. For the purposes of this study's thermal analysis, wood is considered as the material for the lateral walls of the Toda hut.

A simplified model that includes the interior volume and material thickness of the hut—80 mm thick wooden lateral walls and 300 mm thick roof made of 200 mm thick outer straw and 100 mm thick inner bamboo layer—is created as the input geometry for thermal analysis based on the detailed CAD model (Fig. 5.).

2.2.2. Preparation of the 3-D model for the Cube geometry

A hollow cube with an edge dimension of 3.16 metres and the same interior volume as the model Toda hut is also created in CAD to conduct thermal analysis. The results are then compared to the indigenous Toda dwelling. The cube comprises 150 mm thick concrete slabs for the ceiling/floors and 250 mm thick brick walls for the exterior. This Cube model represents a conventional dwelling unit commonly found in mainstream communities.

2.2.3. Material selection for the hut and the cube geometry

Two material properties—thermal conductivity and specific heat capacity—have been considered for the hut and the cube geometry. Wood, soil, bamboo, and straw are used in hut geometry, whereas brick and concrete are used in cube geometry. The materials properties for the thermal analysis are procured from various sources [10–13] and are listed in table 1.

Table 1. Thermal conductivity and specific heat capacity for materials utilised in the thermal analysis.

Material	Thermal Conductivity (*W/mK*)	Specific Heat Capacity (*J/Kg K*)
Wood	0.173	2310
Soil	0.9	545
Bamboo	0.227	1500
Straw	0.086	1694
Brick	1.0	840
Concrete	1.2	880
Air	0.0242	1006.4

2.2.4. External temperature input for analysis

The hourly weather data of Ooty for the years 2020 and 2100 has been generated using the 'Meteonorm 7.3' software based on the B1 scenario, one of the four SRES (Special Report on Emissions Scenarios) [14] families. Meteonorm is a global climate-based tool which generates weather data for a representative year for any location on earth, based on the past data from multiple weather stations. B1 scenario represents a globalised world with rapid economic changes comprising service and information economy, resource-efficient and clean technologies and reductions in material intensity [14]. B1 is considered amongst A1, A2, B1, and B2 scenarios, as it embodies global solutions to sustainability reflective of cooperative endeavours amongst various nations. The generated hourly dry-bulb temperature for the specified years has been segregated day-wise from the weather files. Following which three days of the year have been identified for the thermal analysis: a) the hottest day (i.e., the day of the year exhibiting the highest hourly temperature), b) the coldest day (i.e., the day of the year exhibiting the lowest hourly temperature), and c) the day with the highest difference between the daily maximum and minimum temperatures (i.e., the day of the year exhibiting high range in temperature).

2.2.5. Heat conduction through a solid

The underlying equation governing the conduction of heat through a solid [15] is given as follows:

$$k\nabla^2 T + q = \rho c\, \partial T/\partial t \tag{1}$$

where,
k is the thermal conductivity (in W/mK),
T is the temperature (in K),
t is the time,
q is the rate of heat flux inside the volume (in W),
ρ is the density of the material (in Kg/ m^3), and
c is the material's specific heat (in J/Kg.K). [8]

2.2.6. Boundary conditions

The boundary condition for the analysis of the hut geometry involves the external surface of the roof and the lateral walls being applied with the temperature variation corresponding to the specified days—the hottest day, the coldest day, and the day with a high range in temperature—for 2020 and 2100. The same boundary conditions have been applied to the cube's external wall and roof surfaces. An initial temperature of 22 degrees Celsius has been set as a default temperature for the interior air volume for both the hut and the cube geometries.

A cylindrical body with a diameter of 0.3 metres and a height of 1.65 metres has been placed in both hut and cube geometries and subjected to a constant internal heat generation of magnitude 2 W/m^3, simulating the presence of a human occupant. Thermal analysis for the two geometries with specified external conditions has been conducted, considering the presence or absence of a human inhabitant. The total number of scenarios for the thermal analysis is 24, as highlighted in Table 2.

Table 2. Scenarios for thermal analysis

Years	Days of the Year	Geometry	Presence of human inhabitants	Total number of scenarios for thermal analysis
2020, 2100	Hottest Day, Coldest Day, Day with a high-temperature range	Toda hut, cube	Yes, No	2 x 3 x 2 x 2 = 24

2.2.7. Analysis parameters

The duration of each analysis is 24 hours, and the number of steps involved for each scenario is 24 since it is based on the hourly data of the applied external temperature. Equal time intervals are provided for each step, but further computation subdivisions are software-controlled because this study's primary focus is the internal air's temperature range. Post analysis, the internal air temperature variation for different scenarios is generated and plotted against time.

2.2.8. Assumptions

Only the heat transfer through conduction across the wall and roof material of the geometry is considered. Any effect of internal or external air movements or convection is not considered. Hence fenestrations are not included in the input geometries for the thermal analysis. Furthermore, the impact of humidity and any heat gain or loss due to radiation from the geometry is not taken into account.

The cylindrical abstraction of the human occupant is modelled to continuously emit heat at a rate of 2 W/m^3 for this analysis. Though the average heat generation from a human body can be significantly different from the specified value—depending on the activity and state of the human inhabitant—the provided value is kept minimal to investigate the effect of minor internal heat generation in the thermal analysis. Even though a family of more than one human typically resides in a Toda hut, for the sake of simplicity, only one human is considered.

2.3. CFD analysis methodology for Toda hut

A transient CFD (Computational fluid dynamics) analysis has been performed in Ansys Fluent to assess the airflow patterns and air velocity inside the traditional Toda hut. Two scenarios were analysed: (1) when the hut's door and window are both open, especially during the day, and (2) when the door is closed, but the window is open. The following steps have been adopted to conduct the CFD analysis in Ansys.

2.3.1. Creation of a unified air volume

A unified air volume has been created for the analysis, comprising the interior volume of the Toda hut and the immediate space outside the hut's external surface bounded within an imaginary cuboidal volume (or a bounding box geometry). The bounding box's dimensions follow the hut's exterior measurements along the corresponding axes.

Two variations of the unified air volume (representative of the two scenarios mentioned above) have been created, where the indoor air volume is connected to the unified volume through: — a) two locations (i.e., through the door and window of the hut) and b) one location (i.e., only through the window).

2.3.2. Setting up the boundary conditions

The boundary conditions for the CFD analysis comprise the designation of velocity inlet, pressure outlets and walls in the model. An air velocity of 1m/s is applied at one of the lateral faces of the bounding box (i.e., the external volume), which acts as the velocity inlet face. The corresponding opposite face of the bounding volume acts as a pressure outlet, with the gauge pressure being nil. The exteriors of the bounding box and the external surfaces of the hut model are designated as walls, where the air velocity is 0 m/s.

K-epsilon model, which is the turbulence model selected by default, with the values of *k* and *epsilon* being 5 and 10, respectively, has been employed for this analysis. Other considerations for the model were: a) time steps = 100, b) time interval per step = 1s, and c) iterations per step = 1000. The mesh creation for the air volume was software-controlled. In the CFD's output, the air velocity vector is plotted on a longitudinal plane that passes through the centre of the hut, and the air velocity magnitude at the centroid is estimated.

2.4. VR application for Toda hut

The VR application considers the design of the virtual world (including the Toda settlement), movement in the virtual world, and dealing with interactable objects in the VR world. The interactable object comprises the dashboard—positioned inside a virtual Toda hut in the VR environment—for user input and display of the Toda hut's indoor temperatures and air-velocity magnitude. The design of the virtual world involves the assembly of the terrain surface, 3-D models of vegetation, and 3-D CAD models of Toda huts using a game development platform 'Unity'.

The movement inside the virtual world is facilitated by the downward rotation of the user's head (i.e., a person with a Head Mounted Display experiencing the VR), which results in the forward translation of the user's camera in the virtual environment. The logic for the movement is given as follows:

FUNCTION every frame
  IF camera rotation angle about X axis > threshold angle **AND** camera rotation angle about X axis < 90
    MOVE a character controller bearing camera as a child in (forward direction of the camera * walking speed magnitude)
  END IF
END FUNCTION

The dashboard, which is the interactable object in the VR application, consists of a user input menu and a display panel. In the user input menu, users can select buttons related to years/days/time, result generation and resetting input by gazing at them. A gaze pointer was implemented using a ray with origin on the 'Main Camera' object in Unity with the direction along the 'forward' vector of the 'Main Camera'. Activation of the buttons is achieved using the 'Pointer Enter' event type in Unity, allowing users to select the buttons by positioning the gaze pointer on them through head movements. Upon activation, the 'SHOW' button displays the Toda hut's indoor temperatures and corresponding external temperatures in a 3-D bar graph on the adjacent Display panel. The bar graphs representing external and internal temperatures are unit cube objects in Unity, scaled axially along the Y direction based on the simulated temperature values. The graphs representing the external and internal airflows are represented through two circular objects, with their radii corresponding to the magnitudes of the average external and internal air velocities. Upon activation, the 'RESET' button de-selects any previously-selected buttons in the menu and resets the display panel. The logic for the visualisation of the indoor air parameters is as follows:

CREATE array *et* with hourly external temperature values in order
CREATE array *it* with hourly indoor temperature values in order
FUNCTION every frame
  IF button year no. selected
    IF button day type **AND** button time of day **AND** button SHOW selected
      SCALE cube Ext Temp along Y by *et*[i=0]
      SCALE cube Int Temp along Y by *it*[i=0]
    END IF
    (Repeat IF block for other day type and time of day buttons)
  END IF
  (Repeat IF block for other year no. buttons)
END FUNCTION

3. Results and Discussion

The findings are organised into three subsections: the results of the thermal analysis performed with Ansys; the output of CFD simulations in Ansys; and the developed VR application.

3.1. Results from the thermal analysis

Figures 6 and 7 present the thermal analysis output for the hottest day, coldest day, and day with a high range of temperatures for the years 2020 and 2100. This output includes the variation in the internal air temperature of the hut and cube geometries, both in inhabited and uninhabited states. Further, Table 3 reveals the values for: — a) the difference between the daily minimum temperature and concurrent internal air temperature of the specified scenarios(Δt_m), b) the difference between the daily maximum temperature and concurrent internal air temperatures(Δt_M), and c) the internal temperature ranges of the model scenarios (Δt_r).

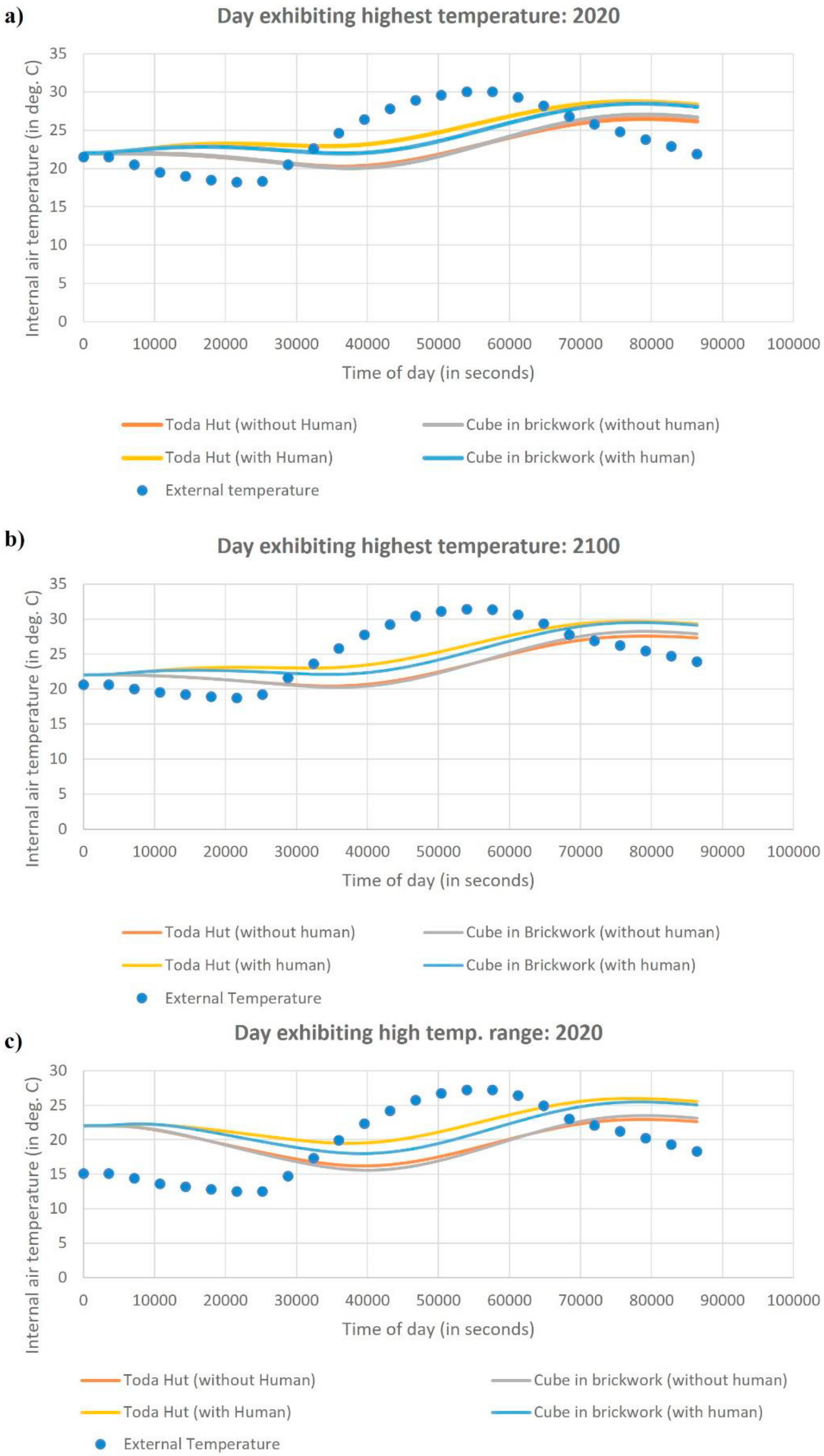

Fig. 6. (a) Internal air temperatures for the hottest day in 2020; (b) Internal air temperatures for the hottest day in 2100; (c) Internal air temperatures for the day with high temperature range in 2020.

3.1.1. Day exhibiting the coldest temperature

It is observed that Δt_m for inhabited Toda hut is 10.69 °C and 10.21 °C, which is 0.85 °C and 0.84°C higher than Δt_m of inhabited Cube, for the day exhibiting the lowest temperature in 2020 and 2100, respectively (Fig. 8.). Also, Δt_r for inhabited Toda hut is 5.71 °C and 5.27 °C which is 2.01 °C and 1.95°C lower than that of the inhabited cube, for the coldest day of 2020 and 2100, respectively. A higher value of Δt_m implies how much warmer the interior of a dwelling is when the external daily temperature is at its lowest. The results show that the inhabited Toda hut will be warmer than an inhabited dwelling made up of brickwork and concrete during the coldest hours of the year. Also, the range of temperature variation in an inhabited Toda hut is lower than that of a conventional dwelling, implying that a person in the hut would not experience high fluctuations in the interior temperatures, irrespective of the variations in the external temperatures during the coldest days.

3.1.2. Day exhibiting the highest temperature

Δt_M for the days exhibiting the highest temperature in 2020 and 2100 for the inhabited Toda hut is 4.11 °C and 5.19 °C, and is 1.02 °C and 1.01°C lower than Δt_M of the inhabited Cube, respectively (Fig. 8.). Higher value of Δt_M represents how much the interior air temperature is lower than the daily maximum external temperature. According to ASHRAE standard 55-2017, the temperature can approximately vary between 67 °F (19.44 °C) and 82 °F (27.77 °C) for optimum thermal comfort of the building occupants [16].

Hence the interior temperature for both the geometries lies well within this range during the hottest hours. Ooty exhibits a subtropical highland climate type, so the weather is typically cool and can get colder in the winter. Therefore, providing thermal comfort on the coldest days is more crucial than at any other time. Additionally, it has been noted that for the hottest days in 2020 and 2100, Δt_r for the inhabited Toda hut is 6.79 °C and 7.69 °C, respectively, comparable to that of the inhabited cube.

3.1.3. Day exhibiting high range in temperature

When the external temperature range is 14.70 for the chosen day in 2020, it is observed that the Δt_r for the inhabited Toda hut is 6.50 °C, which is 0.97 °C lower than the Δt_r for the inhabited cube (Fig. 8). Moreover, for a chosen day with an external temperature range of 14.80 in 2100, the Δt_r for the inhabited hut is 0.92 °C lower than the Δt_r for the inhabited cube. A lower Δt_r indicates the experience of lesser extremes in the internal air temperature, regardless of the variations in the outside temperature.

3.2. Preliminary validation of the thermal simulation

The environment data, which included indoor and outdoor air temperatures and relative humidity (RH), was measured using a UNI-T UT333 BT temperature metre in order to study two full-scale Toda hut models, one at NAWA, Kotagiri, and the other at Tribal Research Centre (TRC), Ooty. For the NAWA model, the temperature readings were taken at 2:00 and 4:00 PM on April 10, 2020, and at 11:00 AM for the TRC hut model. Table 3 highlights the differences in the air temperatures between the observed sensor values and simulated values for outdoors and indoors. It was observed that the error percentage for the indoor air varied from -2% to +3.5%, where the simulation values came from the thermal simulations, whereas the outdoor temperature error varied from -2.8 % to +9.9 %, where the simulation values used the Meteonorm generated weather data. It should be noted that the error percentages are below 10 for all cases, thus validating the preliminary thermal simulation model.

3.3. CFD simulations for air movement inside the Toda hut

In scenario 1, when both the door and window are open, the air velocity at the centroid of the hut is around 0.02 m/s while the external air flow is 1 m/s. For scenario 2—irrespective of the external air movement along door-to-window or window-to-door axes—the air velocity at the centroid is 0 m/s. The air velocity plots for scenarios 1 and 2 are represented in figure 10.

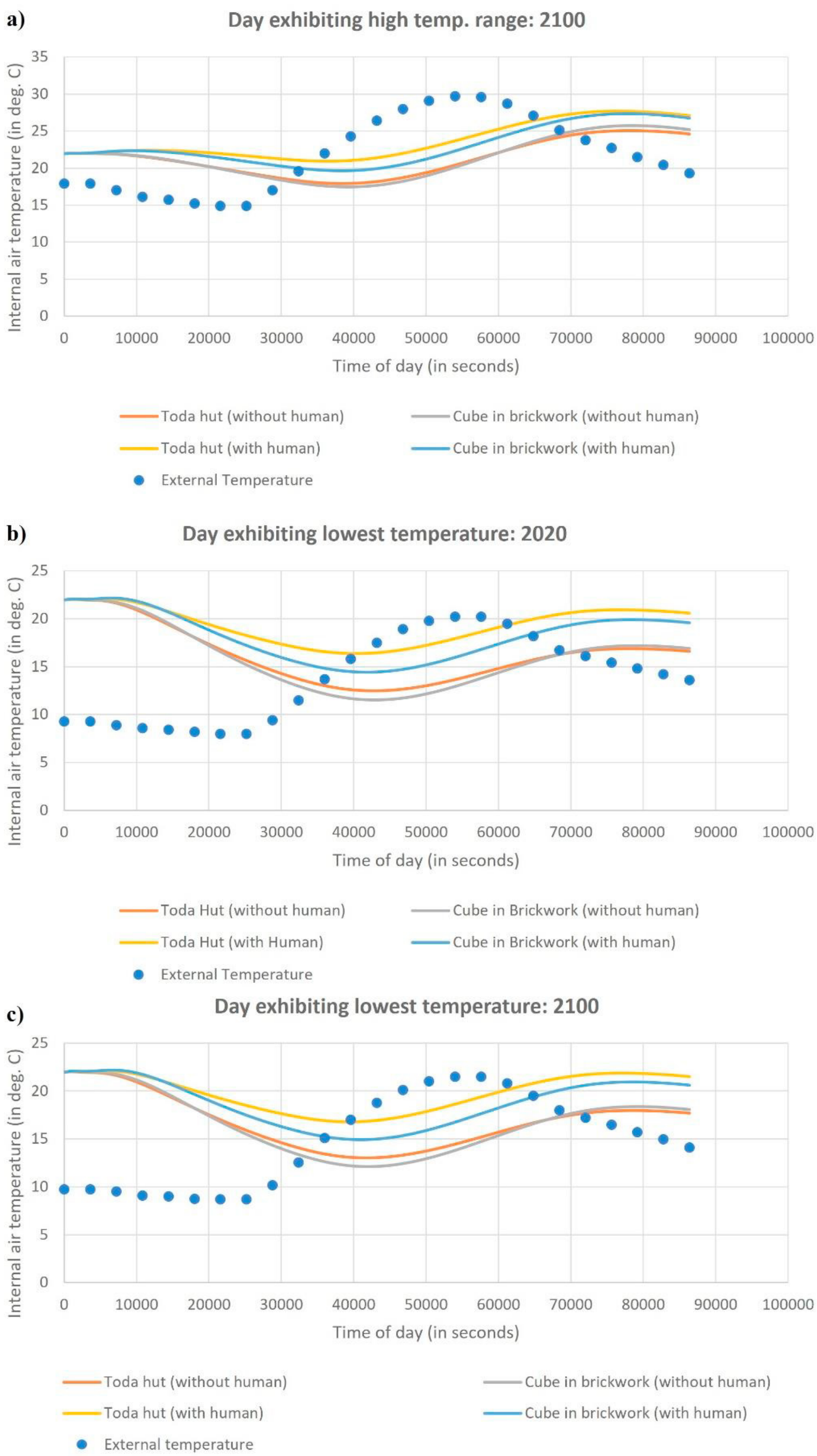

Fig. 7. (a) Internal air temperatures for the day with high temperature range in 2100; (b) Internal air temperatures for the coldest day in 2020; (c) Internal air temperatures for the coldest day in 2100

Table 3. Error % for outdoor and indoor air temperature for 2 Toda hut models.

Temperature (context)	Observed value through the sensor	Predicted value from weather file or thermal simulation	Error (Observed - Predicted)	Error (% of the Observed value)
Toda Hut model at NAWA: External air temperature at 2 PM (℃)	28.8	29.6	-0.8	-2.8
Toda Hut model at NAWA: Internal air temperature at 2 PM (℃)	24.3	24.79	-0.49	-2.0
Toda Hut model at NAWA: External air temperature at 4 PM (℃)	31.5	30	1.5	4.8
Toda Hut model at NAWA: Internal air temperature at 4 PM (℃)	25.71	26.33	-0.62	-2.4
Toda Hut model at TRC: External air temperature at 11 AM (℃)	29.3	26.4	2.9	9.9
Toda Hut model at TRC: Internal air temperature at 11 AM (℃)	23.97	23.122	0.848	3.5

This simulation reflects that the air movement in the interior of the Toda hut is minimal regardless of the external air conditions, on account of the low fenestration area and distinctive hut geometry. These findings are consistent with the requirement to maintain indoor thermal comfort by minimising heat loss through convection and ventilation when the outside temperature falls to a daily minimum.

Taken conjointly, the results of the transient thermal analysis and the transient CFD analysis performed on the Toda hut model, it is quite evident that not only the indigenous building materials but also the design of the fenestrations aids in maintaining the thermal comfort inside the Toda hut. One limitation of the current study is that the factors of thermal conduction and airflow inside the hut are simulated independently but not simultaneously. Even though the individual analysis demonstrates desirable indoor temperature and air movement levels, the outcome of the combined simulation—involving thermal conduction and air movement in and around the Toda hut—is yet to be realised.

3.4. VR application for exploring Toda Architecture

The VR application allows the user to traverse through a hypothetical Toda settlement comprising several Toda dwelling units (or huts) using VR-enabled HMDs through simple head rotations. The user can also travel 'inside' a Toda hut to explore the interior space and interact with a dashboard (comprising buttons) through head-based gaze input. Once the appropriate buttons are selected through gaze—which changes the button colour—relevant visualisations of the indoor conditions are generated in the display section of the dashboard. Fig. 11 (a) shows a Toda settlement, and Fig. 11 (b) shows the interior of the Toda hut with the interactable dashboard in VR.

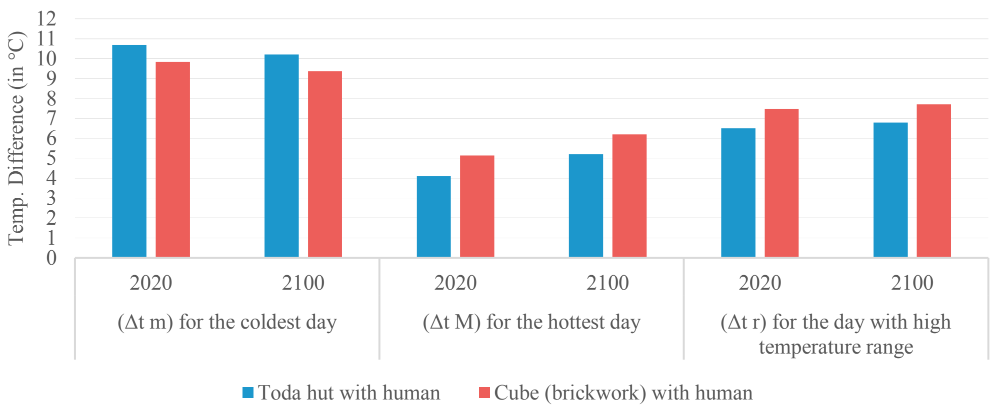

Fig. 8. Temperature difference metrics (Δt_m, Δt_M, and Δt_r) for the coldest day, hottest day, and the day with high temperature range respectively in 2020 and 2100, for inhabited Toda hut and cube geometry in brickwork.

Table 4. Δt_m, Δt_M, and Δt_r for different scenarios in 2020 and 2100

Day Exhibiting Lowest Temperature						
	Difference between the daily minimum temp. and internal air temp. (Δt_m)		Difference between the daily maximum temp. and internal air temp. (Δt_M)		Daily temperature range (Δt_r)	
Year >	2020	2100	2020	2100	2020	2100
External temperature	-	-	-	-	12.20	12.80
Toda hut	8.29	7.83	6.28	6.74	9.57	9.01
Cube (brickwork)	7.98	7.53	6.91	7.31	10.47	9.88
Toda hut with human	10.69	10.21	1.98	2.55	5.71	5.27
Cube (brickwork) with human	9.84	9.37	3.88	4.38	7.72	7.22
Day Exhibiting Highest Temperature						
	Difference between the daily minimum temp. and internal air temp. (Δt_m)		Difference between the daily maximum temp. and internal air temp. (Δt_M)		Daily temperature range (Δt_r)	
Year >	2020	2100	2020	2100	2020	2100
External temperature	-	-	-	-	11.80	12.70
Toda hut	3.15	2.49	6.96	7.99	6.22	7.14
Cube (brickwork)	3.17	2.48	7.01	8.03	7.00	7.98
Toda hut with human	5.03	4.38	4.11	5.19	6.79	7.69
Cube (brickwork) with human	4.54	3.86	5.13	6.20	6.54	7.50
Day Exhibiting High Range in Temperature						
	Difference between the daily minimum temp. and internal air temp. (Δt_m)		Difference between the daily maximum temp. and internal air temp. (Δt_M)		Daily temperature range (Δt_r)	
Year >	2020	2100	2020	2100	2020	2100
External temperature	-	-	-	-	14.70	14.80
Toda hut	6.09	4.82	8.34	9.29	6.73	7.14
Cube (brickwork)	5.93	4.73	8.68	9.59	7.96	8.25
Toda hut with human	8.29	6.93	4.77	6.02	6.50	6.79
Cube (brickwork) with human	7.60	6.30	6.24	7.37	7.47	7.71

3.5. Discussions

The results from the thermal simulations—conducted as a part of implementing the SVA framework for the Toda dwellings—indicate that an inhabited Toda hut provides a warmer environment during colder days than a conventional dwelling in brickwork and concrete even for the future scenario of 2100. An occupant may feel cooler inside a brickwork-based dwelling on the hottest day in 2100, but the indoor temperature provided by the Toda hut during peak external temperatures also lies within the optimal comfort range. Also, compared to a conventional dwelling made of brickwork, a Toda hut experiences less fluctuation in the internal temperature. It implies that a person residing in an indigenous hut would less likely need to rely on an external appliance—like an air conditioner or heater—for thermal comfort. The materials used for a traditional Toda dwelling—like straw, bamboo, wood, and soil, all of which are locally sourced by the members of the Toda community from the nearby forests and natural reserves—and the construction method of the Toda hut aids in maintaining the indoor temperature, without relying on electricity-based active building strategies. Though the thermal analysis model has been preliminarily validated on three instances of sensor data for indoor temperature, the model needs to be validated against a continuous range of sensor data for specific days to assess the overall error of the model. Also, the air velocity inside the Toda hut is minimal irrespective of the external conditions due to smaller fenestrations, which helps maintain thermal comfort in the cool climate of the Nilgiris. Thermal comfort is dependent on many other factors—like humidity, clothing, the metabolic rate of a person, and radiant temperature—apart from air temperature and air speed. Hence, a future study can incorporate temperature and other parameters—including fenestration effects and multiple occupancies—in the thermal analysis model to comprehensively assess indigenous dwellings' thermal comfort.

The SVA framework, comprising data collection, analysis and prediction of data, and data dissemination, has been successfully tested in the context of the traditional Toda dwellings. The vernacular architecture of an indigenous community vulnerable to various external forces of urbanisation and globalisation can be thoroughly assessed using the SVA framework. The data collection function in the SVA framework involves surveying existing structures and monitoring environmental or building parameters in real-time. Such exhaustive data reflects the present condition and throws light on the future state of the building. Monitoring helps keep track of the building state and usage under varying environmental or socio-cultural conditions and over time. The data analysis and prediction function—employing AI or simulation models—helps understand the future performance of the building, apart from its present functionality and performance. Such analysis and predictions would assist policymakers and architects in formulating effective policies or design interventions backed by technology for addressing the core pain points of a community. The data visualisation and dissemination function, involving various interfaces and visualisation techniques, serves the primary function of communicating the collected or analysed data across various stakeholders from different education backgrounds involved in decision making and policy formulation. Immersive (VR) visualisation of space and performance parameters has four key advantages:—a) documenting spatial and functional aspects of indigenous settlements leading to preservation of the vernacular architecture knowledge, b) educating students and other stakeholders about the existence, morphology and construction processes of indigenous architecture by immersing them in a virtual environment, c) creating awareness and interest about the present condition, advantages, and threats to the vernacular architecture through relevant visualisations, and d) to visualise and critically assess a proposed intervention involving habitation, before implementing in the real world. VR in the present study primarily aids in documenting the climate resilient character and performance of the Toda hut apart from education and awareness about the spatial aspects of the Toda architecture. The SVA framework can be potentially implemented to other indigenous communities in different geographical contexts. The framework can then assume a more detailed character incorporating guidelines, exceptions and procedures for assessing the architecture and settlement of any community.

The proposed SVA framework needs rigorous testing and meticulous implementation in real-world scenarios for other indigenous settlements. A detailed implementation strategy for the SVA framework is presented in Fig. 9, which includes the following steps: a) mapping of settlements and tribal communities at the country and regional levels; b) identifying vulnerable communities for SVA-based assessments and interventions; c) the establishment of the Policy Formulation Task Force (PFTF), which develops guidelines for the implementation wing known as the Grassroots Intervention Team (GIT) active on the ground; d) the creation of the GIT, which executes interventions in a specific community following the PFTF's guidelines; e) the creation of the Stakeholder Engagement Team (SET), which makes it easier for different groups and stakeholders to communicate with the SVA's implementation bodies. The GIT would involve relevant stakeholders at the settlement/village level, including the indigenous community representatives, thus paving the way for community-led participatory design. On the other hand, PFTF—acting at a macro level—comprises diverse stakeholders from governmental organisations to technology partners and academics for effectively employing technology and formulating appropriate policies. The implementation strategy would be a hybrid one that incorporates both a top-down strategy as seen in the operation of the PFTF and a bottom-up strategy as seen in the operation of the GIT, which involves feedback to the PFTF and employs community-led participatory design. Such a hybrid strategy for the SVA framework has the potential to identify and solve complex issues concerning the particular indigenous community, as it is inherently based on continual and synchronous information exchange and feedback amongst various stakeholders at different levels.

This study seeks to address the following three sustainable development goals (SDGs): a) SDG 11—making human settlements resilient and sustainable by encouraging the indigenous communities to follow their construction practices; b) SDG 12—ensuring sustainable consumption patterns and reducing waste generated by advocating appropriate construction materials; c) SDG 13—taking action to combat the impacts of climate change, by adopting passive building strategies for thermal comfort.

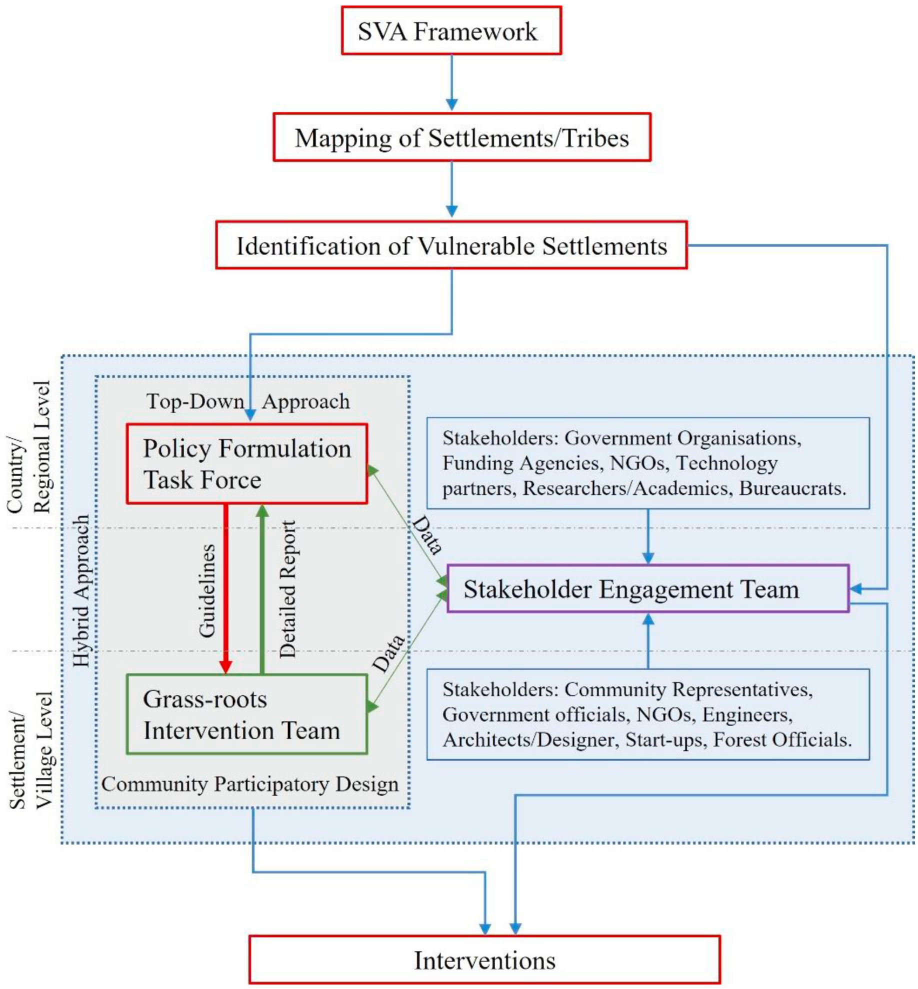

Fig. 9. Detailed Implementation Strategy for SVA Framework

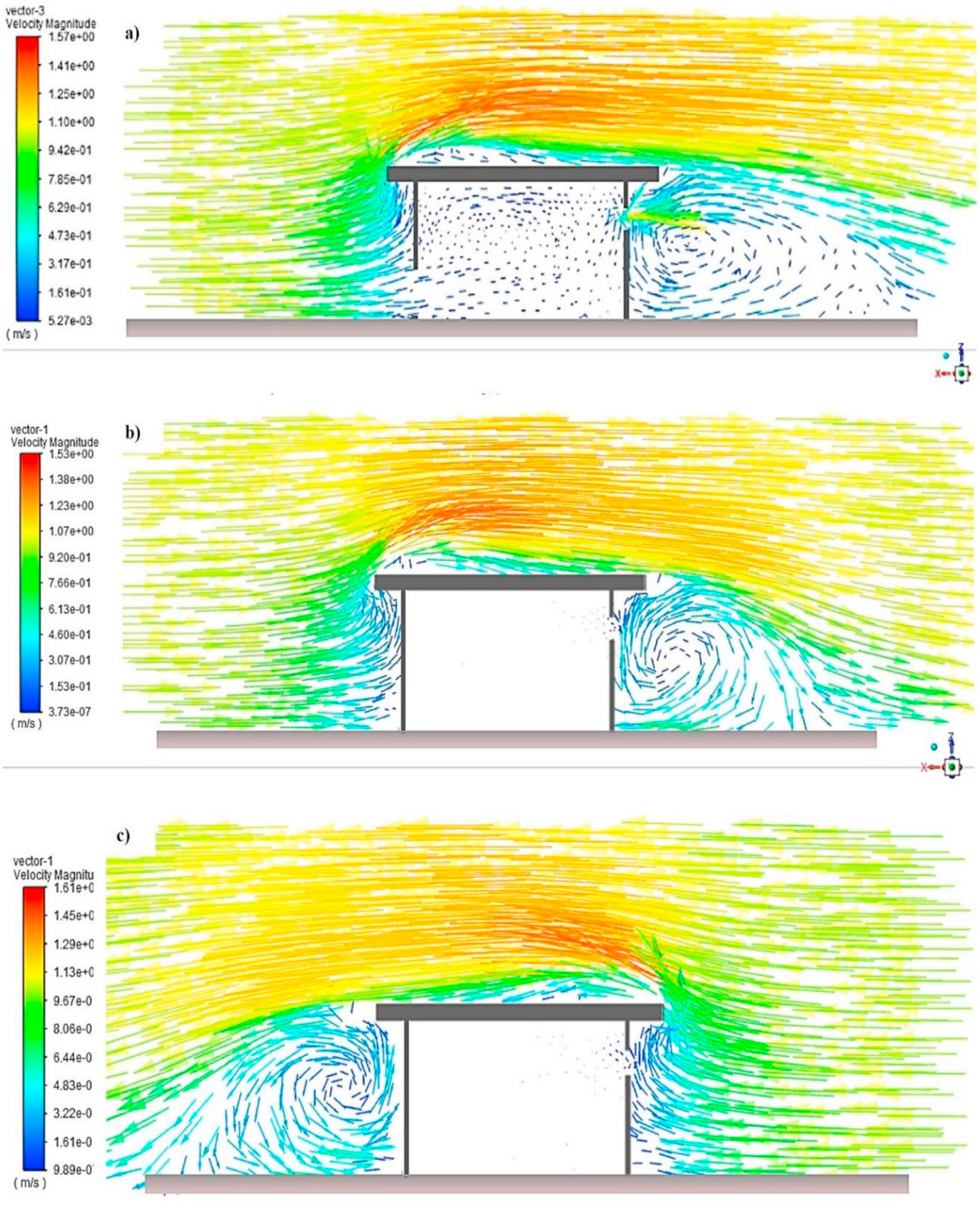

Fig. 10. (a) Air velocity plot for scenario 1, where both door and window are open and external air movement is along the door-to-window axis; (b) Air velocity plot for scenario 2, where only window is open and external air movement is along the door-to-window axis; (c) Air velocity plot for scenario 2, where only window is open and external air movement is along the window-to-door axis.

Fig. 11. (a) Hypothetical Toda settlement in VR; (b) Toda hut interior and dashboard in VR

4. Conclusion

This paper proposes the SVA framework, which enables a researcher to collect, analyse, predict and represent data related to vernacular built forms using emergent technologies. The SVA framework has been tested on Toda dwellings, leading to an evaluation of their indoor comfort based on airflow and indoor temperature using CFD and thermal simulations. The paper also highlights the climate-resilient nature of the Toda huts by simulating and comparing its indoor air temperature with a conventional cube-shaped dwelling in brickwork for the year 2100. The findings from this study indicate that an inhabited Toda hut outperforms a cuboidal brickwork building to keep its occupants warm during the colder months and sustain a more consistent temperature throughout the day. The CFD simulation of the Toda hut also highlights negligible airflow in the interior, thus conserving heat generated by the inhabitants in the colder months. Finally, the SVA framework banks upon the role of Virtual Reality (VR) to showcase the spatial and performance aspects of the Toda dwellings in an immersive and interactive manner. By presenting information about vernacular architecture in an appealing way, VR aims to spark research interest and preserve the knowledge of indigenous dwellings and their functionality for the current and future generations. Since vernacular materials and construction methods have multiple environmental and socio-economical advantages, a policy maker or an architect should promote the preservation of such traditional knowledge regarding indigenous communities' architecture and settlement planning; thus facilitating the continuity of their existing social fabric and ensuring their sustainable development.

References

[1] Rivers, William Halse (1906) "The Toda People", in William Halse Rivers (eds) *The Todas*, London, Macmillan and Co Limited

[2] Noble, William A. (1966) "Toda dwellings and temples." *Anthropos* **61**: 727–736.

[3] Brown, Robert, and Daniel Maudlin. (2012) "Concepts of vernacular architecture." *The SAGE Handbook of Architectural Theory*: 340–355.

[4] Zhai, Zhiqiang John, and Jonathan M. Previtali. (2010) "Ancient vernacular architecture: characteristics categorisation and energy performance evaluation." *Energy and buildings* **42(3)**: 357–365.

[5] Rajapaksha, Indrika, Francesco Fiorito, Estelle Lazer, and Francesca Sartogo. (2018) "Exploring thermal comfort in the context of historical conservation. A study of the vernacular architecture of Pompeii." *Architectural Science Review* **61(1-2)**: 4–14.

[6] Zhong, Wenzhou, Tong Zhang, and Tetsuro Tamura. (2019) "CFD Simulation of Convective Heat Transfer on Vernacular Sustainable Architecture: Validation and Application of Methodology." *Sustainability* **11(15)**: 4231.

[7] Henna, Khadeeja, Aysha Saifudeen, and Monto Mani. (2021) "Resilience of vernacular and modernising dwellings in three climatic zones to climate change." *Scientific Reports* **11(1)**: 1–14.

[8] Hietaharju, Petri, Jari Pulkkinen, Mika Ruusunen, and Jean-Nicolas Louis. (2021) "A stochastic dynamic building stock model for determining long-term district heating demand under future climate change." *Applied Energy* **295**: 116962.

[9] Tootkaboni, Mamak P., Ilaria Ballarini, and Vincenzo Corrado. (2021) "Analysing the future energy performance of residential buildings in the most populated Italian climatic zone: A study of climate change impacts." *Energy Reports* **7**: 8548–8560.

[10] Huang, Puxi, Wen-Shao Chang, Andy Shea, Martin P. Ansell, and Mike Lawrence. (2014) "Non-homogeneous thermal properties of bamboo." *Materials and joints in timber structures*: 657-664.

[11] Costes, Jean-Philippe, Arnaud Evrard, Benjamin Biot, Gauthier Keutgen, Amaury Daras, Samuel Dubois, Frédéric Lebeau, and Luc Courard. (2017) "Thermal conductivity of straw bales: Full size measurements considering the direction of the heat flow." *Buildings,* **7(1)**: 11.

[12] Young, Hugh D. (1992) "University Physics 7th Ed".

[13] "Solids, Liquids and Gases - Thermal Conductivities", Retrieved from https://www.engineeringtoolbox.com/thermal-conductivity-d_429.html. Last accessed 20/07/2022

[14] Nakicenovic, Nebojsa, Joseph Alcamo, Gerald Davis, B. de Vries, Joergen Fenhann, Stuart Gaffin, Kenneth Gregory et al. (2000) "IPCC: Special report on emissions scenarios".

[15] "Intro to Transient Thermal Analysis", Retrieved from https://courses.ansys.com/wp-content/uploads/2020/05/Lesson-1-Introduction-to-transient-analysis.pdf. Last accessed 20/07/2022.

[16] "ASHRAE Technical FAQ", Retrieved from https://www.ashrae.org/File%20Library/Technical%20Resources/Technical%20FAQs/TC-02.01-FAQ-92.pdf . Last accessed 20/07/2022.