Pattern Recognition between the Path of Light and Architectural Elements in Sun Temples of India using Digital Tools: Case of Modhera Sun Temple, Gujarat

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Abstract. This paper explores the intersection of temple heritage and computational analysis by investigating the relationship between sunlight paths and architectural elements in a case of Modhera sun temple in Gujarat. The study decodes the intentional alignment of built elements with solar alignments using digital simulation tools such as Rhino–Grasshopper and the Ladybug plugin. The study employs a two-tiered approach, combining analogical lux meter readings and digital solar path simulations. The research analyses the patterns of solar penetration that occur only during equinoxes, affirming advanced astronomical knowledge embedded in temple design. The methodology combines spatial mapping, digital simulations, and pattern recognition to study how elements like columns, plinths, and shikhara (Main tower above sanctum) control the movement of light through the temple over time. The results demonstrate a deliberate spatial strategy that filters sunlight to illuminate the sanctum on specific celestial dates. This paper contributes to the field of heritage architecture by demonstrating how digital tools can support pattern-based interpretation of ancient knowledge discovery systems embedded in built form.

1 Introduction

Sacred architecture emerged as a medium through which humans encoded their understanding of cosmic forces, particularly celestial bodies, into built form. The sun held a special place, symbolizing divinity and life, and was often central to the design of religious structures. Light is used as a symbolic and experiential element in diverse religious traditions to create meaningful spatial experiences [1].

In Christian and Byzantine churches, light is harnessed to represent the divine through architectural features like clerestories and stained glass. More than fifteen major sun temples exist in India, where sun worship has deep historical roots [2]. Each reflects regional interpretations of a shared cosmological vision. These temples are often located near the Tropic of Cancer, allowing for strategic interaction with sunlight at key times of the year.

Although the focus of this study is the Modhera sun temple in Gujarat (early 11th century CE), its findings resonate with a broader lineage of solar-oriented temple architecture in India. For instance, the Martand Sun Temple in Kashmir (8th century CE) aligns its sanctum to receive direct light during summer solstice dawn. Similarly, the Dakshinaarka Temple in Gaya, Bihar, demonstrates a unique lateral solar ingress. The Konark Sun Temple (13th century CE), although partially in ruins, was originally designed to capture light through a sequence of chariot wheels and columns timed with sunrise during the winter months. These precedents reflect a shared cosmological ethos wherein temple geometry and ritual calendars were integrated through solar alignment [3]. However, the Modhera sun temple is unique for its accurate alignment with the equinox, showing a clear understanding of the changing position of the sun and its importance in sacred architecture. It stands out for its intact structure, detailed carvings, and precise solar orientation. It is believed that on the days of equinox, the first rays of the rising sun enter the temple and directly illuminate the Garbhagriha [4] [5], the innermost sanctum where the deity once resided.

This study explores the Modhera sun temple through the lens of computational heritage analysis. Using digital tools such as Rhino–Grasshopper and the Ladybug plugin [6], along with analogical methods like lux meter surveys, the research investigates how architectural elements—columns, plinths, and shikhara—modulate sunlight through the year [7]. By simulating and verifying the interaction of light with built form, the study identifies recurring spatial patterns and temporal alignments that suggest embedded knowledge systems in the temple's design [8] [9] [10]. By identifying repeating spatial patterns and simulating how sunlight behaves in the temple, this research uses pattern recognition to uncover hidden knowledge in heritage architecture. Sun temples in India represent a unique confluence of religious, astronomical, and architectural symbolism. These temples not only orient toward the sun but are also deeply embedded in mythological, ritualistic, and cosmological narratives.

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1.1 Research design

The research is structured into four main phases: (1) Background Inquiry, (2) Case Study Selection, (3) Documentation and Data Collection, and (4) Analysis. The final analysis was conducted through two distinct but complementary approaches—analogical (on-site measurements) and digital (computational simulation).

1.1.1 Background inquiry: light in sacred architecture

The first phase involved a focused inquiry into the symbolic, ritual, and spatial role of light in sacred architecture, particularly in the context of Indian sun temples. This included an in-depth examination of why such structures are referred to as "sun temples" and how light serves as both a metaphysical symbol and a functional design element in ritual spaces. Emphasis was placed on the integration of sunlight with architectural sequencing, spatial orientation, and timely alignment with celestial events. The investigation traced how light has historically been used in Indian temple architecture to mark celestial events [1] and support ritual practices tied to seasonal cycles. A comparative analysis of prominent Indian sun temples was also conducted, evaluating their geographic coordinates, orientation, construction periods, architectural typologies, materials, and the presence of water bodies. Findings revealed recurring patterns: many temples are located near the Tropic of Cancer (23.5°N), allowing precise solar alignment during equinoxes and solstices; several include adjacent water tanks that emphasize ritual purification and cosmic symbolism. This foundational inquiry helped establish the rationale for selecting the Modhera sun temple as the primary case study and guided the development of a methodology to explore its spatial and solar logic.

1.1.2 Selection of case study

A comparative assessment of major Indian sun temples was conducted to identify a site that could support both empirical and digital analysis. Many temples, while historically important, were either inaccessible, structurally deteriorated, or inadequately documented for computational modelling. Among the better-preserved examples, Modhera sun temple in Gujarat and Konark sun temple in Odisha emerged as potential candidates. However, the Konark temple's scale and inaccessible sanctum limited its feasibility. Modhera was selected for its:

- Intact architectural form and high level of preservation
- Clear equinoctial solar alignment
- Accessibility for detailed on-site measurements
- Suitable scale for accurate 3D modelling and simulation

This combination of historical richness, solar precision, and practical viability made Modhera ideal for a multi-method exploration of light–architecture interaction.

1.1.3 Documentation and data collection

Primary architectural data was obtained from the Archaeological Survey of India (ASI) [11], including dimensional drawings and site reports. These were verified and extended through field surveys, focusing on orientation, spatial hierarchies, and solar access. The verified dataset was digitized and reconstructed in Rhino 3D, using Grasshopper for parametric control. Figure 1 shows that Photogrammetry and LiDAR scanning were employed to ensure geometric fidelity [12] [13]. Neem trees, which offer shade suited to Gujarat's hot-arid climate, supports high-resolution solar simulations [14] [15].

Fig. 1. LiDAR-generated 3D model of modhera sun temple.

1.1.4 Analysis

To decode the interaction between sunlight and temple architecture, a dual-method analytical approach was employed—blending empirical observation with computational simulation.

- Analogical Analysis: Illuminance readings were collected using a lux meter at sunrise, noon, and evening on pre- and post-equinox dates in March. A measurement grid was laid along the east–west axis, covering the Garbhagriha and Nritya Mandapa, to capture spatial variations in light intensity.
- Digital Analysis: Simulations were conducted in Rhino–Grasshopper using Ladybug plugin. Two strategies were applied: (1) inputting azimuth and solar angles manually, and (2) importing EPW climate data to simulate annual sun paths, shadow behaviour, and ray tracing.

This integrated method allowed validation of on-site observations and revealed deliberate design strategies for controlling sunlight [7]. The approach supports pattern recognition and knowledge extraction from heritage geometry, contributing to computational studies in architectural informatics and digital heritage systems.

1.2 Case of modhera

Understanding the historical and geographical context of the Modhera sun temple is essential to decode its architectural and astronomical ingenuity. Located in the town of Modhera, near Mehsana in Gujarat, the site as shown in Figure 2 was formerly known as Mundhera or

Modherpur. The Pushpavati River flows nearby, and the village is situated at an altitude of approximately 66 meters above sea level. According to Jain literature, Modhera was a significant Brahmanical settlement, still recognized today for its traditional religious character. It is also mythologically linked to the marriage of Lord Ram and Sita, with the land said to have been donated as Krishnarapana.

Fig. 2. Site context - case of modhera sun temple.

Strategically located almost directly on the Tropic of Cancer, the temple was designed to align with specific solar alignment, particularly the equinoxes, during which sunlight directly illuminates the sanctum. Built in the early 11th century CE during the reign of Bhimadeva-I of the Solanki dynasty, the temple exemplifies the Maru-Gurjara architectural style and demonstrates a sophisticated understanding of astronomy, geometry, and ritual practice.

The temple is dedicated to Surya Dev, the Sun God, and is considered one of the finest examples of solar architecture in India. Though no longer an active place of worship, it continues to attract scholars, architects, and visitors for its intricate carvings, symbolic spatial planning, and precision in solar alignment. Historians such as Monier Williams, A.K. Forbes, James Burgess, and Henry Cousens have documented its architectural and ritual significance since the late 19th century. In Forbes' account, the sacred water tank (Kund) was referred to as Ram Kund, and the open-pillared dancing hall (Nritya Mandapa) as Sita's chowri (pavilion), establishing mythological connections to the Ramayana.

The spatial logic of the site reveals an intentional effort to channel sunlight into the Garbhagriha (sanctum) on specific solar dates. Such design not only highlights its ritual role but also incorporates astronomical understanding into the architecture. Even today, the urban zoning around the site preserves its solar access: no structure within a 200-meter radius exceeds three storeys, preventing shadows from disrupting the temple's solar geometry.

The Modhera Sun Temple thus serves as a compelling case to explore knowledge-embedded architecture, where solar movement, ritual symbolism, and structural form are intricately interwoven—making it highly relevant for investigation through digital simulation, pattern recognition, and knowledge discovery frameworks.

1.3 Architectural composition

The Modhera sun temple is a remarkable example of symbolic spatial design and intricate craftsmanship. Dedicated to the Sun God, the temple features twelve sculptural representations of Surya on its walls, symbolizing the twelve months of the solar year [5] and reflecting a cyclical conception of time [4]. Other deities, including Vishnu, Ganesha, and Kubera, further enrich the temple's layered spiritual cosmology. Constructed entirely from locally sourced sandstone, the temple integrates seamlessly with its arid surroundings, demonstrating both environmental responsiveness and a strong regional identity [15] circular corbelled dome… rises to a height of 7.6 meters above the temple floor—hallmarks of traditional Indian temple architecture [16].

Fig. 3. Site plan.

In Figure 3, A marks the entry and ticket counter to the temple complex. Adjacent to it, B indicates the restaurant, which is accessible externally. The museum, labelled C, houses recovered sculptures and architectural fragments from the site and the region. D refers to the restrooms, accessible internally, while E denotes the visitor parking area. Flanking the main approach path is a 4.16-acre green buffer zone, populated with native flora—notably Neem trees, which offer shade suited to Gujarat's hot-arid climate. This green belt also sustains local biodiversity, attracting birds such as peacocks, crows, and squirrels, contributing to the ecological character of the temple environment.

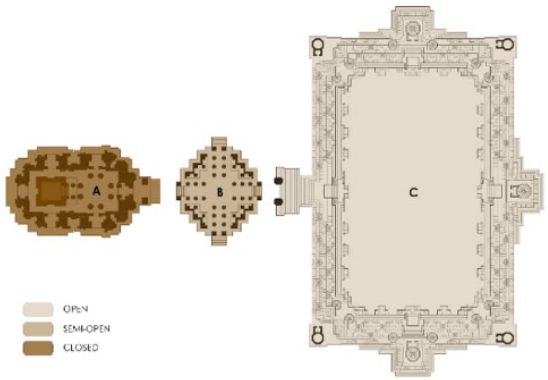

Fig. 4. Temple plan.

As shown in Figure 4, the temple complex is composed of three major architectural components. 1) C- The Surya kund (Ram kund) – a stepped water tank 2) B- the Nritya mandapa or the dancing hall, and 3) A- the main temple shrine that houses the Garbhagriha or

sanctum. These elements are aligned along a linear east–west axis and reflect a ritual and symbolic spatial hierarchy: transitioning from open (Kund), to semi-open (Mandapa), to fully enclosed (Shrine). This sequence reinforces the sacred progression from public interaction to intimate spiritual experience. Between the Kund and the Mandapa once stood a Kirti stambha—a monumental freestanding pillar. Though partially collapsed today, remnants of the lotus-carved base are still visible, exemplifying the sculptural detail embedded in transitional elements.

1.3.1 The main temple shrine

The main temple shrine has an elongated rectangular plan, longer along the north–south axis and richly carved with depictions of various deities. The structure measures approximately 19.10 meters in length (north–south) and 11.60 meters in width (east–west), measured from the plinth level. Two prominent niches (A and B), as shown in Figure 5, divide the plan into two principal zones: the Gudhamandapa (assembly hall) on the eastern side, and the Mulaprasada, including the Garbhagṛiha, on the western side. Each niche is approximately 1.15 meters deep and 1.80 meters wide. Internally, these two sections form near-square chambers, maintaining proportional balance in the spatial layout.

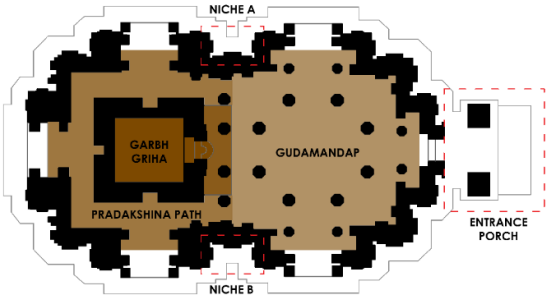

Fig. 5. Main temple shrine plan.

As shown in Figure 6, the temple structure includes three distinct types of pillars supporting the superstructure. The first type comprises eight octagonal pillars located centrally within the Gudhamandapa. They form the structural core beneath the circular corbelled dome. This dome, which culminates in an inverted lotus motif, rises to a height of 7.6 meters above the temple floor. The spacing between the pillars varies slightly—approximately 1.63 meters between the intermediate pillars and 1.8 meters at the cardinal points. They reflect both structural logic and symbolic alignment. The first type of octagonal pillars stands at a total height of 3.8 meters, transitioning into a circular profile at the upper half. The second type, also octagonal but slightly smaller in scale, is positioned directly in front of the inner chamber - Garbhagṛiha. These pillars share similar design elements, base, capital, and bracket motifs.

However, they exhibit a distinct ornamental approach: while the lower half remains relatively plain, the upper portion is richly carved. This selective articulation may relate to low light conditions in this part of the temple, where only the upper segments receive indirect natural light through screened openings. It guides visual focus to the illuminated carvings.

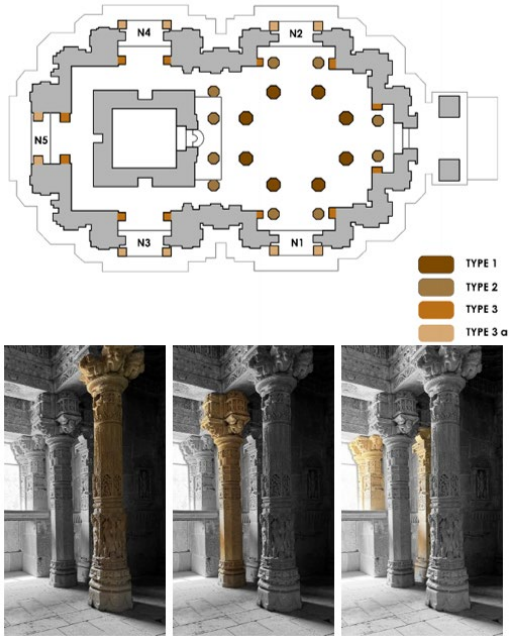

Fig. 6. Types of pillars in the main temple shrine.

The third type of pillar comprises square-section columns, each measuring 0.44 × 0.44 meters, positioned directly against the interior walls. In addition, two dwarf pillars are placed within the external niches of the window screens. These square pillars are smaller in scale compared to the other columns found throughout the temple complex and appear to serve a more supportive and ornamental function within the architectural composition.

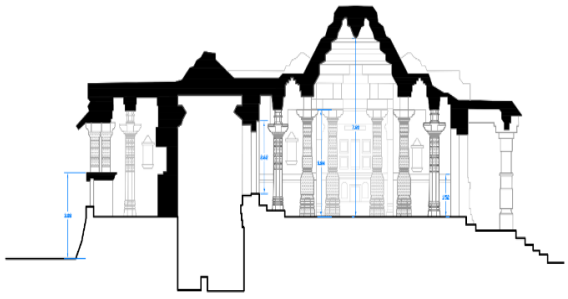

Fig. 7. Temple shrine section.

As shown in Figure 7, the temple employs three ceiling types, each reflecting functional and spatial hierarchy. The central corbelled dome above the Gudhamandapa with a 5-meter base diameter was reconstructed after its earlier collapse and is now visible in restored form. Four smaller corbelled domes occupy the corners of the Gudhamandapa, while other sections of the temple are covered with flat stone slabs. It is likely that the Garbhagṛiha once had a similar corbelled roof, though no remains survive to confirm this.

Figure 8 illustrates the main entrance and exterior panel composition of the sanctum. The façade features 34 intricately carved niche panels—11 on each of the longer (north–south) sides and 6 on the shorter (east–west) sides. They are grouped in sets of five to form square compositions. These deep-set niches are elevated

along a 1.5-meter high socle beneath the 3.3-meter wall, designed to admit only ambient, diffused light, thereby preserving the sanctity and enclosure of the inner shrine.

Fig. 8. Panelling (left) and entrance (right).

Access to the porch is provided by four steps leading to a platform supported by columns spaced 1.8 meters apart. The main doorway, measuring 1.6 meters wide and 3.1 meters high, conforms to Vaastu principles [8], [18] with proportions that guide the funnelling of early morning light into the sanctum while maintaining symbolic spatial hierarchy.

1.3.2 The dancing hall

The Nritya Mandapa, also referred to as the Rang Mandapa, is an open-pillared hall historically used for gatherings. It continues to host cultural dance and music performances today. The space is organized as an elongated square, with the east–west axis measuring approximately 12.80 meters. Steps are provided on all four sides, allowing multiple points of entry. Each side features four rows of pillars as shown in Figure 9, with the outermost row composed of square pillars, and the three inner rows transitioning to octagonal forms. At the centre, these octagonal pillars form an irregular octagon: the distance between cardinal points is 1.86 meters, while the intermediate spacing measures 1.25 meters.

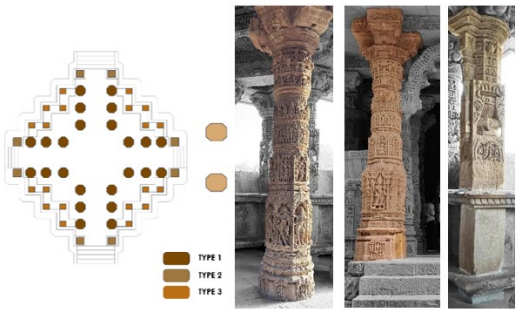

Fig. 9. Types of pillars**.**

Along each side of the raised platform forming the outer boundary, five rectangular pillars (measuring 0.45 × 0.38 m) are placed, each approximately 2 meters in height. In total, the 52 pillars within the hall are believed to symbolically represent the 52 weeks of the solar year. These columns are richly carved, with intricate detailing that reflects the hall's ceremonial and symbolic significance. These are similar to the dwarf pillars of the temple but are different in terms of details. The brackets are in the four directions, which are carved in animal heads. The pillars at the entrance are 3.7 m high. These pillars bear the carving of the deities on each of the four sides of the square plan they are in; the height of these figures is around 0.56 m.

Like the overall temple, the dancing hall features three distinct ceiling types as shown in Figure 10. The centrally corbelled dome above the inner octagon. The ceiling between the columns pairs is slightly corbelled where each of its start at a different height. And the third type of ceiling is between the diagonals of the four corners.

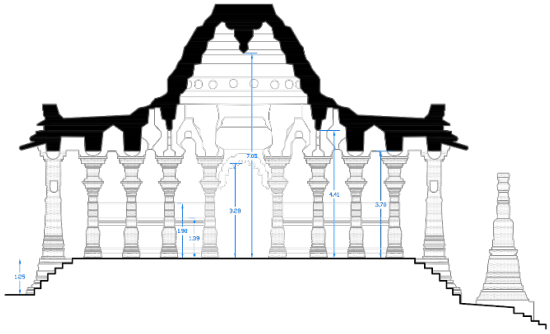

Fig. 10. Dancing hall section.

1.3.3 The water tank

Directly in front of the Nritya Mandapa lies a rectangular sunken water tank, known as the Surya Kund or Ram Kund, measuring approximately 53.35 meters along the north–south axis and 36.5 meters along the east–west axis. Figure 11 shows that the tank is accessed by a series of staggered stairways arranged in a pyramidal configuration, leading down to multiple stepped terraces.

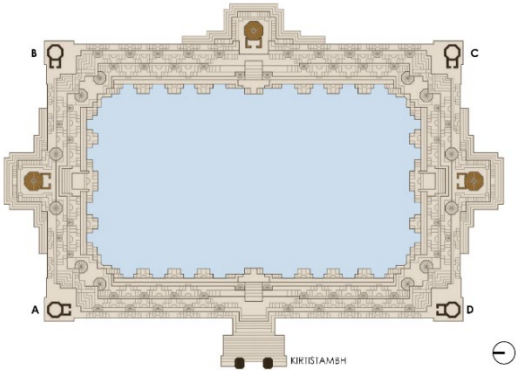

Fig. 11. Water tank.

At the landings of these stairways, small semicircular steps are provided, enhancing movement and visual rhythm. Numerous miniature shrines, embedded into the mid-level terraces, are adorned with reliefs of various deities, contributing to the ritual and symbolic significance of the space. Additionally, rathas (projected shrine-like forms) are found on three sides of the tank, each measuring approximately 4 × 6.8 meters, projecting outward from the rectangular layout. On the four corners, detached shrines are placed at the uppermost terrace, completing the sacred geometry of the tank complex. All the shrines face the tank; they

consist of the Garbhagriha and the Shikhara. There are around 108 shrines in the water tank.

Fig. 12. Shrines.

Figure 12 highlights the 108 miniature shrines surrounding the Surya Kund [19], all oriented inward toward the tank. These shrines hold astrological significance rooted in sacred numerology [17]—such as the sun's diameter being approximately 108 times that of the Earth, and the distance between the Earth and the moon being roughly 108 times the moon's diameter. Though not included in the digital simulations, these features contribute to the temple's cosmological symbolism and reinforce the integration of astronomical knowledge within its spatial design.

2 Methodology

The digital simulations were carried out using Rhino 7 and Grasshopper, integrated with the Ladybug tools plugin suite [6]. For accurate solar data, the EPW file for Ahmedabad (station: 426470, WMO: 426470), being closest to Modhera, was used, corresponding to the temple's geographical location (23.58°N, 72.13°E). Simulations included hourly sun path and radiation analysis using Ladybug's sun Path, Direct Sun Hours, and Radiation Analysis components. The reference plane was defined as the horizontal datum at the Garbhagriha doorway sill level, aligned along the temple's east–west axis. Key simulation parameters included: timestep = 1 hour, grid size = 0.5 m, and an analysis period from March 1 to March 31 to capture the equinoctial window.

Analogical measurements were conducted on-site using a calibrated TESTO 540 digital lux meter. Readings were taken at 15-minute intervals between 6:00 AM and 9:00 AM over multiple days in March 2023. Measurement points included the threshold of the sanctum, the mid-point along the Nritya mandapa axis, and the area outside the main entrance, in order to assess the gradient of light penetration. Environmental conditions during data collection were limited to clear-sky mornings, with ambient temperatures between 22°C and 27°C. Calibration of the lux meter followed ISO standard procedures using a known incandescent source.

To validate the simulation outputs, measured lux values were compared against those derived from Ladybug simulations on March 21 at 6:50 AM. The Root Mean Square Error (RMSE) was found to be 8.66 lux, indicating a strong correlation between digital and analogue methods. Furthermore, the angular deviation between the simulated sun vector and the actual sunrise direction was approximately 2.4°, confirming the accuracy of axial alignment in the model.

2.1 Analogical survey

To assess light interaction within the temple, the study focused on illuminance, the amount of light incident on surfaces, measured in lux. On-site data was collected using a lux meter, and results were compared with digital simulations conducted in Rhino–Grasshopper using Climate Studio. This approach enabled validation of observed lighting conditions against computational predictions, ensuring accuracy in analysing spatial light behaviour.

2.1.1 Process

The lux meter, capable of detecting visible, ultraviolet, and infrared light, was used to measure illuminance levels across the temple complex. Readings were recorded along a defined work plane, ranging from 0.75 m to 1.5 m, spanning from the gateway pillars to the Garbhagriha. In the Nritya Mandapa, the work plane followed the column grid, with the measurement height fixed at 0.9 m above the plinth level. Data was collected on 15th and 21st March 2024—dates surrounding the equinox—at three key time intervals: 7:00 am (sunrise), 12:00 pm (noon), and 6:00 pm (sunset). Approximately 50 readings were taken during each session, focusing primarily along the east–west axis.

To support the analogical data, photographic documentation was conducted during the same time windows and used to validate the simulation results. For accurate 3D reconstruction and cross-verification of architectural drawings, photogrammetry was performed using Luma AI. The close correlation between on-site observations and digital simulations confirmed the reliability of the computational method.

2.2 Digital survey

Digital simulation was employed to analyse how sunlight interacts with the architectural elements of the temple, where celestial alignment plays a critical role. The study utilized Rhino–Grasshopper along with the Ladybug plugin to model and simulate solar behaviour across different times of the year. This approach allowed for the creation of an accurate 3D model and integration of location-specific climate data through EPW files. It enabled the analysis of sunlight paths, shadow patterns, and illumination dynamics. Two simulation methods were adopted: one using manually entered solar angles, and another through Ladybug's automated tools. Together, they provided a reliable framework to assess the relationship between sunlight penetration and spatial configuration. It supported the broader inquiry into embedded astronomical knowledge within the temple's design.

2.2.1 Method 1

To simulate sunbeams, the process began by extracting azimuth and solar elevation angles from the online tool Sun Earth Tools, which provides accurate data on sun position, sunrise/sunset times, and solar paths. A 3D model of the temple was simultaneously developed in Rhino. The extracted solar angles were manually input into a Grasshopper script, allowing for the visualization of sun paths and the projection of sunbeams within the model. This method enabled precise solar simulation without relying on additional plugins, offering a simplified yet effective approach for analysing light movement through architectural space. Solar altitude and azimuth angles were computed to track the sun's position during key equinoctial dates. The following equations were used for reference. Figure 13 illustrate flow chart for method 1.

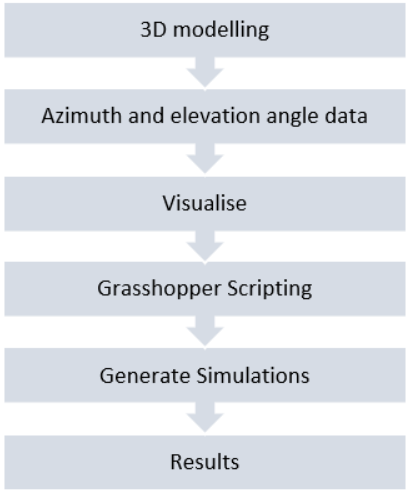

Fig. 13. Flow chart for method 1.

Altitude = $\sin^{-1}$ [$\sin(\delta) \times \sin(\varphi) + \cos(\delta) \times \cos(\varphi) \times \cos(h)$]

Azimuth = $\cos^{-1}$ { [$\sin(\delta) \times \cos(\varphi) - \cos(\delta) \times \sin(\varphi) \times \cos(h)$] ÷ cos(Altitude) }

Where:

δ = Solar declination (°)

φ = Latitude of the site (23.58° for Modhera)

h = Hour angle (°), calculated as 15 × (solar time – 12)

Solar declination and hour angles were derived using NOAA's Solar Calculator and cross-checked with Sun Earth Tools. EPW weather data for Ahmedabad (2023) was used to ensure the accuracy of sunrise timing and sun position inputs.

2.2.2 Method 2

The second simulation method uses the Ladybug plugin within Grasshopper, offering a more comprehensive and automated workflow. After importing the 3D model into Rhino, the script is configured with site-specific coordinates and time parameters, allowing simulation across various days and times throughout the year. The geographic coordinates are sourced from Sun Earth Tools, ensuring accuracy in solar positioning and sunrise/sunset data. Additionally, an EPW (Energy Plus Weather) file is integrated to enrich the simulation with local climate data, including solar radiation, temperature, humidity, and wind conditions. This method enables the generation of sunbeams and analysis of solar penetration patterns, aiding in the interpretation of spatial-light relationships within the temple complex. Figure 14 shows flow chart for method 2.

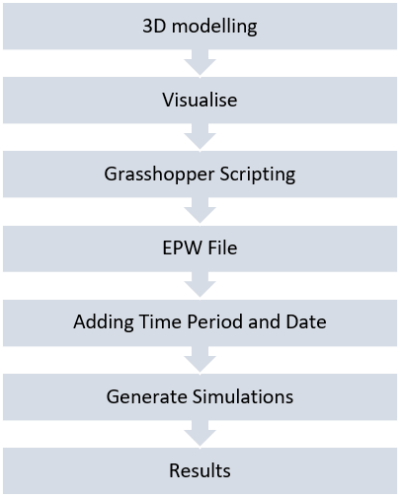

Fig. 14. Flow chart for method 2.

2.3 Validation: analogical vs. simulated data

To validate the accuracy of solar simulations conducted in Rhino–Grasshopper using the Ladybug plugin, a comparative analysis was undertaken against field-measured lux values collected using a TESTO 540 digital lux meter. Data from both sources were aligned to a common grid of reference points marked along the east–west axis of the temple (as illustrated in Figure 16). Measured and simulated illuminance values were compared for the same date and time—21st March 2023 at 6:50 AM—to account for equinoctial alignment and early morning solar ingress.

The Root Mean Square Error (RMSE) was calculated to quantify the deviation between the two datasets as shown in Table 1 below.

3 Results

Multiple sets of results were generated through the analog and digital methods described earlier. These outputs were compared to evaluate how architectural elements interact with light. While only representative results are presented here, the full dataset was collected following the procedures outlined in each section. Once the digital simulations were validated against on-site measurements, additional runs were conducted to explore light behaviour in greater depth and clarity.

3.1 Photo documentation

The first set of results obtained from the on-site observation was done using photo documentation as seen in Figure 15.

The below images are taken on 15th March and 21st March 2024 respectively at 7:00 am. The gate of Garbhagriha is visible in the image. Similar Figure 15.

Analog Lux values reference points documentation was done for 12:00 pm and 6:00 pm on both the days.

Fig. 15. Light falling on the gate of garbhagriha.

3.2 Lux meter readings

The second set of readings on site were taken using the lux meter. As discussed above, the working plane was divided into several points grid along the east-west axis as shown in Figure 16. The accuracy of on-site readings was affected by several limiting factors, including variable cloud cover at different times of the day. It could not be consistently mapped. Additionally, the presence of tourists in the frequently visited temple complex posed challenges to capturing uninterrupted and precise measurements.

Table 1. Comparison of analog and visual simulated lux values at reference points in modhera sun temple (march 15, 2024, 7:00 AM).

Reference Point	Analog (Measured) Lux	Visual Simulated Lux	(Analog - Sim)^2
15	200	0.69	39840.04
16	1847	1.15	3409223.52
17	1436	1.38	2061984.78
18	1305	0.92	1702996.38
19	980	0.23	959407.87
20	672	0.23	451517.13
21	255	0.23	64968.67
22	255	0.23	64968.67

The resulting RMSE of 8.66 lux as shown in Table 1 suggests a close correlation between analog and simulated values, thereby validating the model's reliability in representing early morning light behaviour. Minor discrepancies may be attributed to material reflectance, ambient conditions, and instrument calibration limits.

The validation reinforces that the temple's spatial configuration and orientation accurately align with solar events and can be reliably simulated using climate-based daylight tools. While the simulations primarily use visual ray tracing via Ladybug Tools, the study prioritizes spatial-solar alignment in a heritage context rather than computational optimization. The approach focuses on validating cultural hypotheses through calibrated, time-specific simulations, rather than parametric sensitivity or algorithmic novelty.

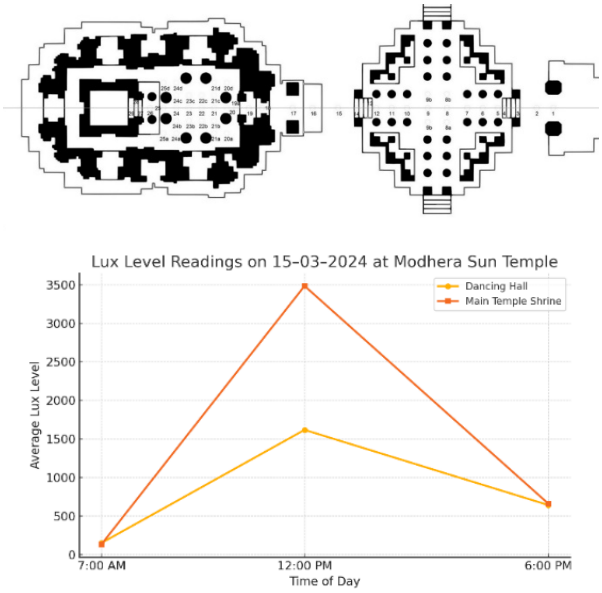

Fig. 16. Lux meter readings at reference points suggested in a map.

3.3 Digital simulation using method 1

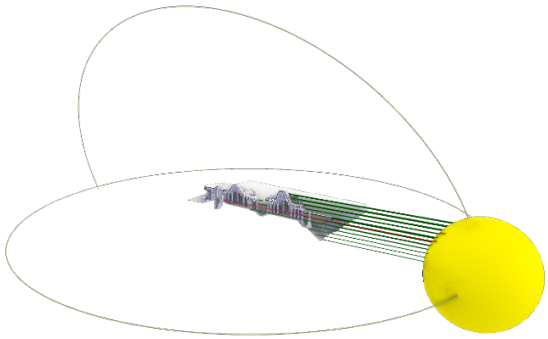

Fig. 17. Simulation result – method 1.

Multiple simulations were conducted to analyse the interaction of sunlight with architectural elements from various angles. These included perspective and sectional views to capture the dynamics of light penetration and obstruction across different parts of the temple. Figure 17 illustrates the simulation results using Method 1, in which solar angles for March 21st at 6:50 AM were manually input into a custom Grasshopper script. In the visualization, the X–Y ring represents the solar orbit, while the curved arc illustrates the sun's trajectory on the selected date. The red ray highlights the longest unobstructed path of sunlight penetrating directly into the Garbhagriha (sanctum sanctorum), thereby confirming a precise axial alignment between the temple's entrance and the sunrise on the equinox. This axial illumination supports the hypothesis of intentional solar targeting. Sectional perspectives further enhance the three-dimensional understanding of this interaction, revealing how the architectural composition—particularly the spacing and orientation of plinths and columns—guides and filters sunlight over time. Additionally, annual simulations were conducted for the 21st day of each month in 2023 to map seasonal variations in solar incidence and examine the broader solar-responsive behaviour of the built form.

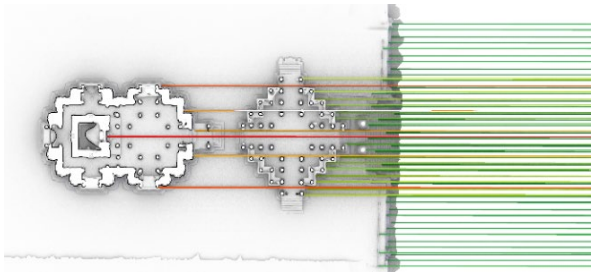

Fig. 18. Zoomed simulation view.

The Figure 18 thus shown has the percentage of light blocked by each element if we consider the number of rays that hit the surface the total existing rays. From the front elevation we see the circles to represent the position where these rays intersect with the surfaces.

The percentage of rays blocked was estimated by counting the number of rays intersecting specific architectural surfaces within the Rhino–Grasshopper environment and dividing this by the total number of rays generated in the simulation domain. These rays were cast at hourly intervals on March 21 using uniform angular spacing and density.

3.4 Digital simulation using method 2

The diagram below illustrates the movement of direct sunlight and the corresponding shadow patterns across the temple complex during three key time slots—morning, noon, and evening. These simulations help analyse the dynamic interplay between light and architecture throughout the day. Notably, the main temple shrine (Garbhagriha) remains largely in shadow during most of the year, receiving direct sunlight only around the equinoxes. This observation reinforces the hypothesis of intentional solar alignment embedded within the temple's architectural design [3]. The simulation result shown in Figure 19.

It is so designed in a way that no amount of direct light will ever enter the main temple except for the equinoxes even though there is presence of openings around the temple. The red patch indicates the maximum direct sun hours while the blue patch is for the minimum. The sectional simulation shown in Figure 20. is generated using Method 2, employing the Ladybug plugin within Grasshopper, to assess the duration and intensity of direct sunlight on the Garbhagriha doorway. The section is aligned along the central dome of the main shrine, passing through key niches to accurately capture spatial light behaviour. The simulation focused on early morning hours (06:00–09:00 IST) using Method 2 (Ladybug plugin with EPW data). The section aligned along the east–west axis of the temple captures solar exposure on the Garbhagriha entrance using a chromatic gradient (red: maximum, blue: minimum). Superimposed solar arcs for March 21st visualize the equinoctial path. Validation was done against photo-documented field data.

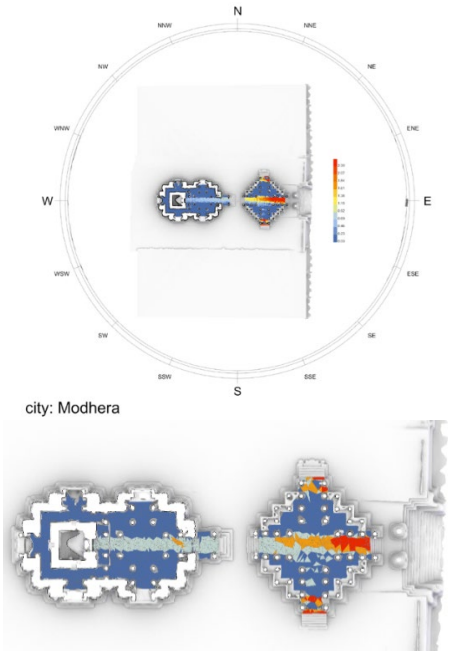

Fig. 19. Simulation result – method 2.

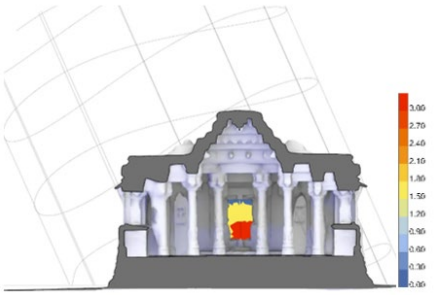

Fig. 20. Sectional simulation output of method 1.

4 Analysis

The sectional simulation illustrated in Figure 20, generated using Method 2 (Ladybug plugin with EPW data), and quantitatively evaluates the duration and spatial extent of direct solar exposure on the Garbhagriha entrance. The section, aligned along the temple's principal east–west axis through the central dome and niches, captures solar interaction during the morning hours (06:00–09:00 IST). The chromatic gradient, ranging from red (maximum exposure) to blue (minimal), visualizes direct sun hours on the entrance surface. Superimposed solar arcs indicate sun paths specific to 21st March, derived from annual EPW-based solar data.

Validation against photo-documented analogical observations confirms the simulation's reliability, with high correlation observed on equinoctial alignment. Extending this method across the month of March enabled the extraction of temporal patterns in solar penetration. Notably, no direct sunlight reaches the doorway before 14th March; gradual ingress begins on the 15th, shifting laterally from right to left, peaking with axial alignment on 21st March (equinox), and declining post 29th March. This recurring temporal-spatial pattern, derived from longitudinal simulation datasets, exemplifies knowledge discovery through

pattern recognition, revealing the temple's calibrated spatial alignment with solar cycles—supporting hypotheses of intentional solar-oriented architectural design.

While the term "pattern recognition" is used in this study, it does not imply the use of computational algorithms such as supervised or unsupervised learning, clustering, or statistical pattern analysis. Rather, it refers to the qualitative identification of recurring spatial-light interactions observed through both analogical and digital methods. This interpretive approach allowed the recognition of repeated equinoctial light paths and architectural alignments, reflecting an embedded design logic rooted in solar cycles. The study focuses on temporal-spatial regularities, not algorithmic recognition.

5 Inference

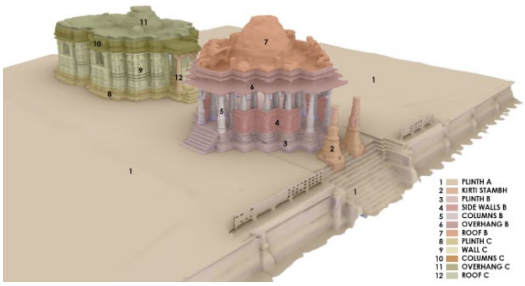

Fig. 21. Sectional simulation result of method 2.

Figure 21 illustrates the spatial segregation and function of architectural elements within the Modhera sun temple complex, emphasizing their role in modulating early morning solar radiation. Based on sunrise simulations during the equinox, approximately 64–70% of incoming solar rays bypass all architectural surfaces, while the remaining 30–36% interact with specific components. These elements—plinths, columns, and walls—are categorized based on their relative contribution to solar obstruction.

The Garbhagriha, conceived as the sanctum sanctorum, receives almost no direct sunlight except during the equinoxes, reinforcing its symbolic role as a sacred, enclosed, and temporally aligned space. In contrast, the Nrityamandapa demonstrates a varied solar filtration throughout the year due to its irregular column spacing, which appears to be purposefully designed to filter or obstruct sunlight depending on solar angle and season.

The primary plinth (A), raised approximately 2.2 meters above ground, emerges as a critical solar modulator. Simulations show it blocks 25–46% of low-angle sun rays during winter mornings, particularly facilitating selective ingress of rays toward the Garbhagriha during the equinox. The secondary plinths (B and C) contribute an additional 5–7% and 0–6% blockage respectively. This cumulative filtering indicates intentional spatial calibration and a nuanced understanding of solar geometry embedded in the temple's design.

The Nrityamandapa accounts for 5% of ray blockage in March and up to 15% in August, with an annual obstruction of 29–39%. Its columns—neither equidistant nor symmetric—perform critical seasonal modulation. This differentiated obstruction pattern suggests a deliberate architectural strategy to vary light ingress across the calendar year. In comparison, the main shrine walls and roof block approximately 6–30% of rays, with peak shading in April.

Table 2 summarizes the monthly simulation findings, identifying the "most efficient" architectural element for solar modulation in each month—based on cumulative obstruction percentages. For example, Walls (C) dominate in January, June, and December, while Columns (B) are most effective from February through May and again in August and October. The Roof (B) plays a prominent role in March and September, the equinoctial months. While digital simulations and analogical observation suggest an axial alignment between sunrise light paths and the Garbhagriha during equinoxes, this interpretation remains hypothetical. No archaeological, inscriptional, or astronomical records definitively confirm intentional solar alignment in this case. The conclusions drawn are based on observable architectural features and present-day solar geometry. To strengthen this hypothesis, further validation through archeoastronomy analysis or comparative studies with other Indian sun temples is recommended.

Overall, the results reflect a deliberate architectural approach where form, elevation, and sequencing orchestrate light and shadow throughout the year. The Garbhagriha, remaining dark except on select days, and the Nrityamandapa, filtering light dynamically through its columns and roof, together create a calibrated solar-temporal experience. This analysis points to a knowledge-driven design logic where solar modulation reinforces ritual meaning and spatial sanctity.

Table 2. Annual analysis.

Month	Most efficient element
January	Walls C
February	Columns B
March	Roof B
April	Columns B
May	Columns B
June	Walls C
July	Columns B & Walls C
August	Columns B
September	Roof B
October	Columns B
November	Walls C
December	Walls C

6 Conclusion

This study demonstrates that the architectural design of the Modhera Sun Temple reflects intentional spatial and solar alignment, rooted in advanced environmental and astronomical awareness. Digital simulations and analogical observations reveal that elements such as the elevated plinth, irregular column spacing, and volumetric sequencing work together to modulate light with temporal precision. The Garbhagriha remains largely in darkness except during equinox.

inox sunrises, indicating deliberate celestial alignment embedded in sacred space design. While the study does not introduce new algorithms, it contributes by applying established simulation tools to validate cultural and spatial knowledge, illustrating how accessible digital methods can reveal embedded design logic with scientific accuracy. Although the methodology is specific to Modhera's spatial context, it offers a transferable workflow. With further abstraction—standardizing inputs (e.g., EPW files), analysis (solar simulation, lux validation), and outputs (alignment patterns)—this approach could evolve into a replicable framework for analysing solar-oriented heritage sites.

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Authors contribution

MC conceptualized the thought and worked on the writing of the paper. FB designed the study and helped in formulation of the pattern recognition and digital analysis. SGP guided the content creation on Sun Temples along with editing. All authors further verified the information, edited the manuscript and detailed the discussion.

Conflict of interest

The authors declare no conflict of interest.

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