

# Strategic Reduction of Solar Radiation through Adaptive Facades in Indore

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## Abstract

Heat gain in buildings is identified as one of the major causes of solar radiation, resulting in indoor discomfort and increased energy demand. This study examines the role of adaptive facades in reducing solar radiation in the composite climate of Indore, characterised by strong seasonal variations. Through sun-path analysis and identification of solar geometry, climate-responsive facade conditions that tackle incident radiation, seasonal sun angle shifts, and low-angled east-west exposure are identified.

Studied facade typologies are categorised into static, rotating, folding, and sliding based on their adaptation mechanisms and material configurations, followed by a qualitative framework that evaluates six criteria, namely, cut-off efficiency, relative radiation blockage, seasonal responsiveness, east-west performance, user control, and maintenance complexity.

The study concludes with a suitability matrix, offering a structured basis for selecting adaptive facade strategies in a composite climate of Indore.

**Keywords:** Adaptive facade, climate-responsive, building envelope, smart skins, energy efficient, building facade, solar radiation, dynamic shading, thermal comfort, dynamic facade

## 1. Introduction

Solar radiation leads to surface heat gain in building envelopes, raising indoor temperature and cooling load requirements (Hosseini et al., 2019). Fixed shading devices work well for the designed angle but fail to track and respond to the seasonal shifts and lower sun positions that characterise the composite climate of Indore (as per ECBC, India) (see Figure. 2). Conversely, Adaptive facades tackle this directly by adjusting and modulating their geometry, opacity, and/or material properties to adapt to variable solar conditions. This, as per Romano et al. (2018), helps in reducing the incident solar radiation before active cooling is needed, thus reflecting a reduce-before-produce approach.

The total heat load on the facade is contributed by a cumulative result of direct, indirect and diffused solar radiation that falls on the building envelope (Kipp & Zonen, 2011). To understand the effectiveness of different facade systems in mitigating this radiation in a composite climate, this study uses the solar geometry of Indore to compare the selected facade typologies: static, rotating, folding, and sliding facades. While research specific to Indore is limited, studies from similar climatic zones indicate that optimisation of facade performance relies heavily on the management of varying solar radiation. Traditional static shading elements like chajjas or louvres block solar radiation for designed sun positions and timings. In contrast, adaptive facades are more effective in blocking variable solar radiation through geometric or optical adjustments (Jamilu et al., 2024).

While adaptive facades have clearly demonstrated the potential to reduce heat gain and energy consumption, there is still a lack of systematic examination of their effectiveness and suitability in composite climates like Indore, which highlights the default use of static facades and their lack of adaptability to tackle variable climatic conditions.

This study addresses the mentioned gap through an in-depth analysis of four facade typologies (static, rotating, folding, and sliding) based on solar geometry, evaluation of their adaptability to Indore's local solar conditions, and their effectiveness in blocking solar radiation.

This is done by mapping solar angles and curves against the adaptive limitations of each typology. Using literature review and solar path analysis, specific facade control requirements are derived. By analysing the adaptation logic of the selected facade typologies, a comparative suitability matrix with a context-specific framework for performance-based facade design is derived.

Findings contribute a detailed, context and solar-geometry-based suitability analysis, extending envelope typology knowledge for performance-based design in composite climates like Indore.

## 2. Literature Review

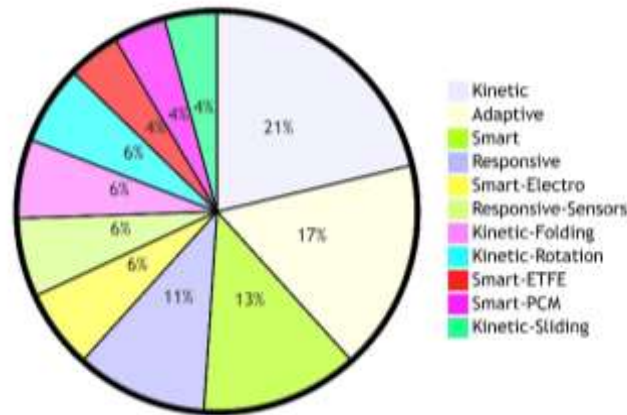
### Adaptive Facades and Typologies

Adaptive Facades mark a significant milestone in building envelope evolution, moving from static facades to a climate-responsive building envelope that reacts and adapts to external environmental conditions to maintain comfortable indoor conditions and reduce energy demand. In composite climatic zones, the performance of static facades in protecting against weather is limited due to their inability to adjust to the solar variations, thus being restricted to a fixed approach. Conversely, Adaptive facades change their properties in response to stimuli like solar radiation or temperature, fulfilling multiple functions like solar shading, daylight control, ventilation, and energy balance.

Romano et al. (2018) analysed over 40 definitions (kinetic, responsive, smart, switchable, etc) to create a system that describes the mechanism and response, establishing differentiation between facade categories such as static (fixed geometry), kinetic (rotation, folding, sliding, or translation), and smart (material-based, e.g., electrochromic glass and Phase Change Materials (PCM)). Kinetic facades are designed with programmed movements that block solar radiation, while in responsive systems, actuators or sensors are used to respond to real-time changes. A superposition matrix was used by Boeke et al. (2021) to evaluate 15 design functions like solar shading, ventilation, etc., along with adaptive capacities of facades, including flexibility, responding time, automation level, etc (see Figure 1). Ultimately, literature establishes adaptive facades as performance mediators rather than aesthetic novelties.

Many studies classify typologies by movement or function, but few compare them systematically. Solar geometry offers a useful basis for comparison because facade efficiency changes with altitude, azimuth, incidence, and shadow angles.

**Figure 1: Studies on Facade Typologies based on Literature Review**  
**Source: Generated by author**



### Solar Geometry as a Facade Evaluation Tool

Facades can be evaluated by estimating their shading efficiencies along the varying solar paths. A rigorous method would be based on solar geometry by analysis of various solar angles that include altitude (ALT), azimuth (AZI), declination (DEC), inclination (INC), and horizontal/vertical shadow angles (HAS/VSA). Static facades tend to be optimal for a single angle but continue to perform poorly at lower angles, leading to excessive glare. Adaptive facades comply with the changing solar geometry through parametric design approaches and performance testing for varying hourly and seasonal scenarios.

Using ALT and AZI inputs (Hosseini et al., 2019) demonstrated that rotation tends to perform better than translation for low-angle solar radiation. Other authors such as (Boeke et al., 2021; Tabadkani et al., 2019) used solar geometry to articulate response time and adaptivity matrix, while Tabadkani et al. simulated solstices and equinoxes to attain UDI curves. The use of solar path diagrams and stereographic projections is highly relevant to quantify obstructions or solar shading for multi-criteria evaluation.

Working with matrices and morphological charts, as seen in most studies, legitimises geometry-based assessment, but most studies apply it to single prototypes without apparent typological comparisons.

### Solar Control in Composite Climates

Indore's composite climate requires a balance between hot-dry summers with evening transitions and winter admissions. Static chajjas or horizontal louvres block the afternoon sun but fail to work in mornings, evenings, or during winters when the sun is lower. Adaptive facades, however, can be programmed to automatically or manually change to reduce heat gain and energy consumption.

In hot and humid climates, (Hosseini et al., 2019) studied a reduction of heat gain by 50-80% in comparison to static facades in Al Bahr Towers and Helio Trace Centre, while (Tahmasbi et al., 2025) states that up to 60% of energy consumption can be saved by using adaptive facades. Additionally, (Jamilu et al., 2024) explain that for tropical and composite zones, geometric adaptations can reduce loads by 27 to 48%. Simulation study of adaptive facade typologies by (Dev & Saifudeen, 2023) Kerala's hot-humid climate suggests a reduction of 25-40% in cooling loads. According to (Bing Song et al., 2022), the impact of long-term solar effects on comfort is quantifiable, promoting solar geometry-aligned systems.

### East-West Facades and Low Angle Radiation

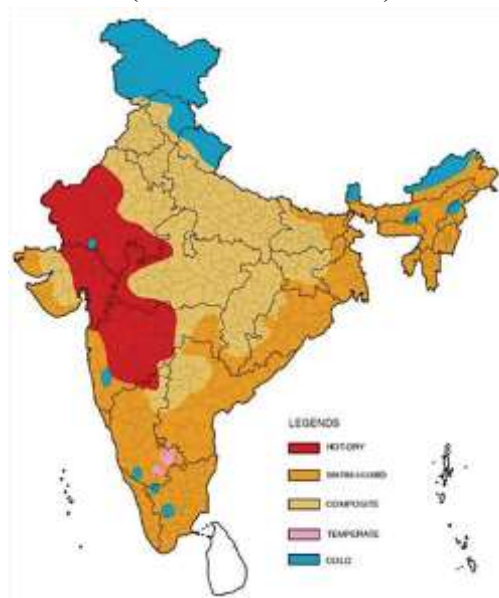
East and west facades experience lower-angle radiation, causing glare and overheating even with high-altitude protection in the south. Automated east-west shading systems reduce glare by 50-80% while reducing lighting consumption by 20 to 48% (de la Barra et al., 2025). In a composite climate like Indore's, west-facing facades align with peak heat and low ALT and can be tackled similarly through adaptive facades.

Although the role of geometry in solar control has been validated in adaptive facades, it primarily focuses on singular studies, metrics, simulations, or general reviews with no cross-comparison of typologies in variable conditions in composite climatic contexts like Indore.

### 3. Study Context and Study Unit Specification

Indore is chosen because its composite climate (see Figure 2) has strong seasonal variation, making solar control a major design requirement. To evaluate the efficiency of the selected facade typologies in this climatic context, this study isolates a 1m x 1m unshaded vertical window as a standardised study unit to avoid real-world complexities and structural geometries. By dissociating the building envelope from any specific building dimensions, floor heights or urban obstructions, the study focuses entirely on how varying orientations interact with local regional solar geometry. This limitation allows to examine and compare the solar gain, shading performance, and orientation effects in a controlled way before an in-depth solar climate analysis. To enable comparison and analysis of different facade typologies, this study unit will be studied across eight major orientations: North, North-East, East, South-East, South, South-West, West, and North-West.

**Figure 2: Climatic zones of India**  
(ECBC, India, 2018)



### 4. Solar Climate Analysis

Indore's climate produces a changing solar pattern across seasons and times of day. Using the site latitude of 22.76°N, the study analyses solstices, equinoxes, and three daily timestamps, 9:00 AM, 12:00 PM, and 3:00 PM, to establish the basis for solar-angle calculations.

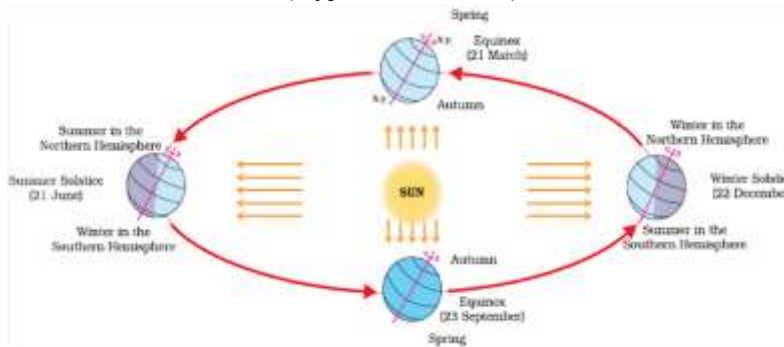
Minimum temperature- 8.1°C (IndianClimate.com)  
 Annual precipitation- 1060 mm (World Weather & Climate Information)  
 Mean Relative Humidity- 53.3% (IndianClimate.com)

This section uses manual geometric calculations to determine solar path and shading angles that will be used further to assess various facade typologies. Site-specific latitude of 22.76°N is used to determine the exposure patterns.

**Selected Dates and Timings**

The chosen dates and timings (Table 1) represent and provide a comprehensive analysis of the solar extremes to understand and determine the maximum shading demand, optimal solar admission, and the transitional baseline of the annual sun path (see Figure 3 & Figure 4).

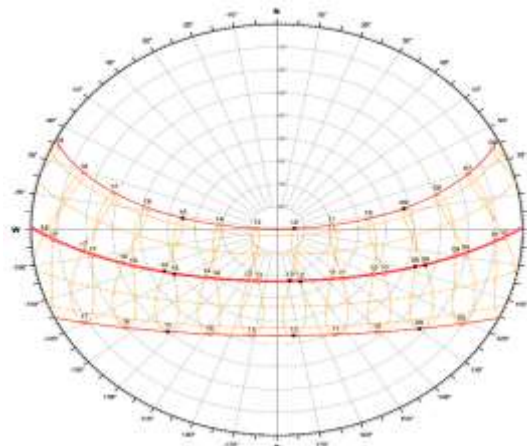
**Figure 3: Annual Earth Revolution Diagram**  
 (Byjus.com, 2021)



**Table 1: Selected date and day of the year**

Solar Event	Date	Day of the Year (NDY)	Condition
Spring Equinox	March 21	80	Transitional condition
Summer Solstice	June 22	173	Worst case of solar exposure
Vernal Equinox	September 23	266	Transitional condition
Winter Solstice	December 22	356	Solar admission is desired

**Figure 4: Sun path diagram representing the key days and timings**  
 (Dr Andrew J. Marsh, 2014, edited by the author)



**Geometric Framework and Calculations**

The analytical framework used in this study follows (Steven V. Szokolay, 1996)’s methodology. The solar geometry is the key determinant of a building’s facade performance, establishing the timing and solar heat intensity across different orientations.

Step 1: Declination Angle (DEC)

It represents the earth’s tilt relative to the sun and is calculated using the formula below, derived by Cooper in 1969, where NDY represents the Day of the Year.

$$DEC = 23.45 \times \sin [0.986 \times (284 + NDY)] \tag{1}$$

Using the same formula, Table 2 is derived.

**Table 2: Declination angles of selected dates**

Solar Event	Date	Day of the Year (NDY)	Declination Angle (DEC)	Analysis
Spring Equinox	March 21	80	≈ 0	Directly over the equator, equal day and night globally
Summer Solstice	June 22	173	≈ +23.45°	Maximum declination towards the sun. Sun highest, maximum radiation
Vernal Equinox	September 23	266	≈ 0	Directly over the equator, equal day and night globally
Winter Solstice	December 22	356	≈ -23.45°	Maximum declination away from the sun. Sun lowest, minimum radiation

Step 2: Hour Angle (HRA)

$$HRA = 15 \times (\text{hour} - 12) \tag{2}$$

Calculated HRAs are displayed in Table 3.

Step 3: Solar Altitude (ALT) and Azimuth (AZI)

The solar position at any given time is defined by two primary angles: the angle of the sun above the horizon, called the altitude (ALT), and the horizontal angle from North, called the azimuth (AZI). The values are derived from the formulas below.

$$ALT = \sin^{-1}(\sin DEC \times \sin LAT + \cos DEC \times \cos LAT \times \cos HRA) \tag{3}$$

&

$$AZI = \cos^{-1}[(\cos LAT \times \sin DEC - \cos DEC \times \sin LAT \times \cos HRA) \div \cos ALT] \tag{4}$$

For the afternoon, the following rule is applied:

$$AZI_{noon} = 360 - AZI \tag{5}$$

Table 3 displays all the calculated values in a consolidated manner.

**Table 3: Solar Altitudes & Azimuths of selected days and timestamps**

Solar Event	Date	DEC	Time	HRA	ALT	AZI	Direction
Spring Equinox, Vernal Equinox	March 21,	0°	09:00 AM	-45°	40.70°	111.15°	ESE
	September 23		12:00 PM	0°	67.24°	180.00°	S

			03:00 PM	+45°	40.70°	248.85°	WSW
Summer Solstice	June 22	+23.45°	09:00 AM	-45°	48.78°	79.86°	ENE
			12:00 PM	0°	89.31°	0.00°	N
			03:00 PM	+45°	48.78°	280.14°	WNW
Winter Solstice	December 22	-23.45°	09:00 AM	-45°	26.37°	133.61°	SE
			12:00 PM	0°	43.79°	180.00°	S
			03:00 PM	+45°	26.37°	226.39°	SW

**Vertical and Horizontal Shadow Angles**

Step 1: Horizontal Shadow Angle (HSA) (Table 4)

$$HSA = AZI - ORI$$

(Steven V. Szokolay, 1996) (UN-Habitat, 2018) (6)

**Note:** If |HSA| is between 90° and 270°, then the facade is in shade, and the sun is behind the facade.

If HSA is greater than 270° then;

$$HSA = HSA - 360° \tag{7}$$

If HSA is less than -270° then;

$$HSA = HSA + 360° \tag{8}$$

**Table 4: Horizontal Shading Angles (HSA) of selected days and timestamps**

Orientation	Time	Summer Solstice HSA		Equinoxes HSA		Winter Solstice HSA	
North (0°)	09:00 AM	79.86°		111.15°	Shaded	133.61°	Shaded
	12:00 PM	0°		180°	Shaded	180°	Shaded
	03:00 PM	-79.86°		248.85°	Shaded	226.39°	Shaded
North-East (45°)	09:00 AM	34.86°		66.15°		88.61°	
	12:00 PM	-45°		135°	Shaded	135°	Shaded
	03:00 PM	235.14°	Shaded	203.85°	Shaded	181.39°	Shaded
East (90°)	09:00 AM	-10.14°		21.15°		43.61°	
	12:00 PM	-90°	Shaded	90°	Shaded	90°	Shaded
	03:00 PM	190.14°	Shaded	158.85°	Shaded	136.39°	Shaded

<b>South-East (135°)</b>	09:00 AM	-55.14°		-23.85°		-1.39°	
	12:00 PM	-135°	Shaded	45°		45°	
	03:00 PM	145.14°	Shaded	113.85°	Shaded	91.39°	Shaded
<b>South (180°)</b>	09:00 AM	-100.14°	Shaded	-68.85°		-46.39°	
	12:00 PM	-180°	Shaded	0°		0°	
	03:00 PM	100.14°	Shaded	68.85°		46.39°	
<b>South-West (225°)</b>	09:00 AM	-145.14°	Shaded	-113.85°	Shaded	-91.39°	Shaded
	12:00 PM	-225°	Shaded	-45°		-45°	
	03:00 PM	55.14°		23.85°		1.39°	
<b>West (270°)</b>	09:00 AM	-190.14°	Shaded	-158.85°	Shaded	-136.39°	Shaded
	12:00 PM	-270°	Shaded	-90°	Shaded	-90°	Shaded
	03:00 PM	10.14°		-21.15°		-43.61°	
<b>North-West (315°)</b>	09:00 AM	-235.14°	Shaded	-203.85°	Shaded	-181.39°	Shaded
	12:00 PM	45°		-135°	Shaded	-135°	Shaded
	03:00 PM	-34.86°		-66.15°		-88.61°	

Step 2: Vertical Shadow Angle (VSA) (Table 5)

$$VSA = \tan^{-1} \left[ \frac{\tan(ALT)}{\cos(HSA)} \right] \quad (\text{Steven V. Szokolay, 1996}) \quad (\text{UN-Habitat, 2018}) \quad (9)$$

**Table 5: Vertical Shading Angles (VSA) of selected days and timestamps**

Orientation	Time	Summer Solstice VSA	Equinoxes VSA	Winter Solstice VSA
<b>North (0°)</b>	09:00 AM	81.23°	-67.24°	-35.71°
	12:00 PM	89.31°	-67.24°	-43.79°
	03:00 PM	81.23°	-67.24°	-35.71°
<b>North-East (45°)</b>	09:00 AM	54.29°	64.82°	87.20°
	12:00 PM	89.51°	-73.48°	-53.59°
	03:00 PM	-63.40°	-43.24°	-26.38°
<b>East (90°)</b>	09:00 AM	49.23°	42.68°	34.40°
	12:00 PM	90°	90°	90°
	03:00 PM	-49.23°	-42.68°	-34.40°
<b>South-East (135°)</b>	09:00 AM	63.40°	43.24°	26.38°

	12:00 PM	-89.51°	Shaded	73.48°		53.59°	
	03:00 PM	-54.29°	Shaded	-64.82°	Shaded	-87.20°	Shaded
<b>South (180°)</b>	09:00 AM	-81.23°	Shaded	67.24°		35.71°	
	12:00 PM	-89.31°	Shaded	67.24°		43.79°	
	03:00 PM	-81.23°	Shaded	67.24°		35.71°	
<b>South-West (225°)</b>	09:00 AM	-54.29°	Shaded	-64.82°	Shaded	-87.20°	Shaded
	12:00 PM	-89.51°	Shaded	73.48°		53.59°	
	03:00 PM	63.40°		43.24°		26.38°	
<b>West (270°)</b>	09:00 AM	-49.23°	Shaded	-42.68°	Shaded	-34.40°	Shaded
	12:00 PM	90		90°		90°	
	03:00 PM	49.23°		42.68°		34.40°	
<b>North-West (315°)</b>	09:00 AM	-63.40°	Shaded	-43.24°	Shaded	-26.38°	Shaded
	12:00 PM	89.51°		-73.48°	Shaded	-53.59°	Shaded
	03:00 PM	54.29°		64.82°		87.20°	

### Solar Radiation

Indore’s climate is characterized by seasonal fluctuations, with peak radiation occurring in the pre-monsoon months of April and May.

Table 6 shows the annual Global Horizontal Irradiance, highlighting the periods of maximum thermal stress.

**Table 6: Global Horizontal Irradiance (GHI) of Indore**  
(Generated using Solar Irradiance Calculator by BAESS Labs, 2026)

Month	Global Horizontal Irradiance (GHI) (kWh/m <sup>2</sup> /day)
January	4.72
February	5.66
March	6.47
April	7.03
May	7.07
June	5.57
July	4.65
August	4.52
September	5.59
October	5.61
November	4.79
December	4.34
Annual	5.51

Step 1: Angle of Incidence (INC) (Table 7)

$$INC = \cos^{-1}(\sin ALT \times \cos TIL + \cos ALT \times \sin TIL \times \cos HSA) \tag{10}$$

where TIL stands for the tilt angle of the receiving plane from the horizontal

For vertical planes, since TIL = 90,  $\cos TIL = 0$ ,  $\sin TIL = 1$

$$INC = \cos^{-1}(\cos ALT \times \cos HSA) \tag{11}$$

**Table 7: Angle of Incidence**

Direction	Time	Summer Solstice			Equinoxes			Winter Solstice		
		HSA	ALT	INC	HSA	ALT	INC	HSA	ALT	INC
North (0°)	09:00 AM	79.86°	48.78°	83.34°	111.15°	40.70°	<b>105.87°</b>	133.61°	26.37°	<b>128.18°</b>
	12:00 PM	0°	89.31°	89.31°	180°	67.24°	<b>112.76°</b>	180°	43.79°	<b>136.21°</b>
	03:00 PM	-79.86°	48.78°	83.34°	248.85°	40.70°	<b>105.87°</b>	226.39°	26.37°	<b>128.18°</b>
North-East (45°)	09:00 AM	34.86°	48.78°	57.27°	66.15°	40.70°	72.15°	88.61°	26.37°	88.75°
	12:00 PM	-45°	89.31°	89.51°	135°	67.24°	<b>105.88°</b>	135°	43.79°	<b>120.70°</b>
	03:00 PM	235.14°	48.78°	<b>112.12°</b>	203.85°	40.70°	<b>133.89°</b>	181.39°	26.37°	<b>153.60°</b>
East (90°)	09:00 AM	-10.14°	48.78°	49.56°	21.15°	40.70°	45.01°	43.61°	26.37°	49.55°
	12:00 PM	-90°	89.31°	<b>90°</b>	90°	67.24°	<b>90°</b>	90°	43.79°	<b>90°</b>
	03:00 PM	190.14°	48.78°	<b>130.44°</b>	158.85°	40.70°	<b>134.99°</b>	136.39°	26.37°	<b>130.45°</b>
South-East (135°)	09:00 AM	-55.14°	48.78°	67.87°	-23.85°	40.70°	46.10°	-1.39°	26.37°	26.40°
	12:00 PM	-135°	89.31°	<b>90.49°</b>	45°	67.24°	74.12°	45°	43.79°	59.30°
	03:00 PM	145.14°	48.78°	<b>122.72°</b>	113.85°	40.70°	<b>107.85°</b>	91.39°	26.37°	<b>91.25°</b>
South (180°)	09:00 AM	-100.14°	48.78°	<b>96.66°</b>	-68.85°	40.70°	74.13°	-46.39°	26.37°	51.82°
	12:00 PM	-180°	89.31°	<b>90.69°</b>	0°	67.24°	67.24°	0°	43.79°	43.79°
	03:00 PM	100.14°	48.78°	<b>96.66°</b>	68.85°	40.70°	74.13°	46.39°	26.37°	51.82°
South-West	09:00 AM	-145.14°	48.78°	<b>122.72°</b>	-113.85°	40.70°	<b>107.85°</b>	-91.39°	26.37°	<b>91.25°</b>

<b>(225°)</b>	12:00 PM	-225°	89.31°	<b>90.49°</b>	-45°	67.24°	74.12°	-45°	43.79°	59.30°
	03:00 PM	55.14°	48.78°	67.87°	23.85°	40.70°	46.10°	1.39°	26.37°	26.40°
<b>West (270°)</b>	09:00 AM	-190.14°	48.78°	<b>130.44°</b>	-158.85°	40.70°	<b>134.99°</b>	-136.39°	26.37°	<b>130.45°</b>
	12:00 PM	-270°	89.31°	<b>90°</b>	-90°	67.24°	<b>90°</b>	-90°	43.79°	<b>90°</b>
	03:00 PM	10.14°	48.78°	49.56°	-21.15°	40.70°	45.01°	-43.61°	26.37°	49.55°
<b>North-West (315°)</b>	09:00 AM	-235.14°	48.78°	<b>112.12°</b>	-203.85°	40.70°	<b>133.89°</b>	-181.39°	26.37°	<b>153.60°</b>
	12:00 PM	45°	89.31°	89.51°	-135°	67.24°	<b>105.88°</b>	-135°	43.79°	<b>120.70°</b>
	03:00 PM	-34.86°	48.78°	57.27°	-66.15°	40.70°	72.15°	-88.61°	26.37°	88.75°

Step 2: Radiation load on each facade ( $I_{FACADE}$ ) (Table 8)

$$I_{FACADE} = GHI \times \cos INC \tag{12}$$

**Table 8: Radiation load on each facade**

Direction	Time	Spring Equinox (March 21) (GHI= 6.47 kWh/m <sup>2</sup> /day)		Summer Solstice (June 22) (GHI= 5.57 kWh/m <sup>2</sup> /day)		Vernal Equinox (September 23) (GHI= 5.59 kWh/m <sup>2</sup> /day)		Winter Solstice (December 22) (GHI= 4.34 kWh/m <sup>2</sup> /day)	
		INC	$I_{FACADE}$	INC	$I_{FACADE}$	INC	$I_{FACADE}$	INC	$I_{FACADE}$
<b>North (0°)</b>	09:00 AM	<b>105.87°</b>	-1.77	83.34°	0.65	<b>105.87°</b>	-1.53	<b>128.18°</b>	-2.68
	12:00 PM	<b>112.76°</b>	-2.50	89.31°	0.07	<b>112.76°</b>	-2.16	<b>136.21°</b>	-3.13
	03:00 PM	<b>105.87°</b>	-1.77	83.34°	0.65	<b>105.87°</b>	-1.53	<b>128.18°</b>	-2.68
<b>North-East (45°)</b>	09:00 AM	72.15°	1.98	57.27°	3.01	72.15°	1.71	88.75°	0.09
	12:00 PM	<b>105.88°</b>	-1.77	89.51°	0.05	<b>105.88°</b>	-1.53	<b>120.70°</b>	-2.22
	03:00 PM	<b>133.89°</b>	-4.49	<b>112.12°</b>	-2.10	<b>133.89°</b>	-3.88	<b>153.60°</b>	-3.89
<b>East (90°)</b>	09:00 AM	45.01°	4.57	49.56°	3.61	45.01°	3.95	49.55°	2.82
	12:00 PM	<b>90°</b>	0	<b>90°</b>	0	<b>90°</b>	0	<b>90°</b>	0

	03:00 PM	<b>134.99°</b>	-4.57	<b>130.44°</b>	-3.61	<b>134.99°</b>	-3.95	<b>130.45°</b>	-2.82
<b>South-East (135°)</b>	09:00 AM	46.10°	4.49	67.87°	2.10	46.10°	3.88	26.40°	3.89
	12:00 PM	74.12°	1.77	<b>90.49°</b>	-0.05	74.12°	1.53	59.30°	2.22
	03:00 PM	<b>107.85°</b>	-1.98	<b>122.72°</b>	-3.01	<b>107.85°</b>	-1.71	<b>91.25°</b>	-0.09
<b>South (180°)</b>	09:00 AM	74.13°	1.77	<b>96.66°</b>	-0.65	74.13°	1.53	51.82°	2.68
	12:00 PM	67.24°	2.5	<b>90.69°</b>	-0.07	67.24°	2.16	43.79°	3.13
	03:00 PM	74.13°	1.77	<b>96.66°</b>	-0.65	74.13°	1.53	51.82°	2.68
<b>South-West (225°)</b>	09:00 AM	<b>107.85°</b>	-1.98	<b>122.72°</b>	-3.01	<b>107.85°</b>	-1.71	<b>91.25°</b>	-0.09
	12:00 PM	74.12°	1.77	<b>90.49°</b>	-0.05	74.12°	1.53	59.30°	2.22
	03:00 PM	46.10°	4.49	67.87°	2.10	46.10°	3.88	26.40°	3.89
<b>West (270°)</b>	09:00 AM	<b>134.99°</b>	-4.57	<b>130.44°</b>	-3.61	<b>134.99°</b>	-3.95	<b>130.45°</b>	-2.82
	12:00 PM	<b>90°</b>	0	<b>90°</b>	0	<b>90°</b>	0	<b>90°</b>	0
	03:00 PM	45.01°	4.57	49.56°	3.61	45.01°	3.95	49.55°	2.82
<b>North-West (315°)</b>	09:00 AM	<b>133.89°</b>	-4.49	<b>112.12°</b>	-2.1	<b>133.89°</b>	-3.88	<b>153.60°</b>	-3.89
	12:00 PM	<b>105.88°</b>	-1.77	89.51°	0.05	<b>105.88°</b>	-1.53	<b>120.70°</b>	-2.22
	03:00 PM	72.15°	1.98	57.27°	3.01	72.15°	1.71	88.75°	0.09

Table 8 shows the radiation load on each facade orientation. When the INC is between 26° and 50°,  $I_{FACADE}$  is the highest, whereas a high INC drops the  $I_{FACADE}$  towards zero or negative, indicating that the facade is shaded. East and west facades record the highest radiation received during the spring equinox at 9:00 am and 3:00 pm, respectively. The same is observed during the vernal equinox. Although facing identical solar angles, the west facade is prone to overheating due to positive loads received throughout the afternoon across all seasons, combined with the high ambient air temperature outdoors. Similarly, the south-west facade represents a high prolonged exposure zone across the equinoxes and winter solstice. South facade, although receiving radiation throughout the studied days, except the summer solstice, the intensity received remains lower than that received by the east and west facades.

This proves that static facades fail to tackle variable seasonal conditions. Due to the constantly shifting sun path, a fixed shading device either causes under-shading when protection is required and overshading when passive heat gain is needed. This orientation-specific variability establishes the need for typology-specific facade responses evaluated in the following sections.

### 5. Facade Typologies and Adaptation Logic

Building facades, being the primary environmental barrier between the interior and exterior, play an important role in regulating solar radiation, heat, daylight, and ventilation. Adaptive facades, unlike static facades, can adapt in response to the variable solar conditions of Indore.

In this study, static facades are considered the basic condition against which the adaptive typologies (rotating, folding, and sliding) are compared, following Dev & Saifudeen (2023)’s methodology. Within the three adaptive typologies, the axis of movement, horizontal or vertical, determines which solar angle each system intercepts. To be specific, a horizontal axis helps orient shading to manage the solar altitude (ALT), whereas a vertical axis adjusts to handle the solar azimuth (AZI). This distinction directly governs facade suitability across Indore’s eight orientations. Table 9 provides a consolidated overview of all typologies and sub-types before each is discussed in detail.

**Table 9: Facade Typology Classification**

Typology	Sub-Type	Solar Angle Addressed	Adaptation Mode	Suitable Orientations in Indore
<b>Static</b>	Horizontal (Chajja/Louvres)	ALT	Fixed	S
	Vertical (Fins)	AZI	Fixed	E, W
<b>Rotating</b>	Horizontal	ALT	Angular Tracking	S, SE, SW
	Vertical	AZI	Angular Tracking	E, W, NE, NW
<b>Folding</b>	Horizontal	ALT	Area and depth change	S, SE, SW
	Vertical	AZI	Area change	E, W, NE, NW
<b>Sliding</b>	Horizontal	ALT	Partial surface coverage	S, SE, SW
	Vertical	AZI	Partial lateral coverage	E, W, SE, SW

#### Static Facades

Static facades use fixed shading devices to block solar radiation, with no ability for seasonal and diurnal adjustments. In Indore, this typically takes the form of reinforced concrete chajjas (horizontal projections) or fixed vertical and horizontal louvres. Their shading performance depends entirely on alignment with the sun angles for which they were designed.

**Figure 5: Chajja**



**Figure 6: Vertical fins**



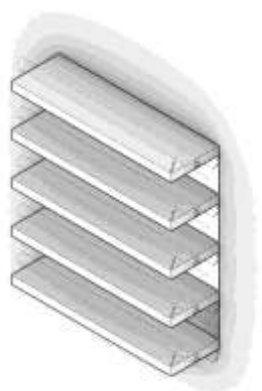
Horizontal (Chajja/Louvres) (see Figure 5): These are designed using the VSA to intercept high-altitude radiation on south-facing surfaces. It blocks the design ALT effectively, but fails to adjust to seasonal variations (Jamilu et al., 2024). At Indore’s winter solstice noon ALT of  $43.79^\circ$  (Table 3), the same overhang that blocks summer radiation also cuts useful solar admission. It provides no AZI response, making it completely ineffective on East and West orientations. These are suitable as a low-cost shading device on south facades (Hosseini et al., 2019).

Vertical (Fins) (see Figure 6): They intercept laterally arriving radiation at the set AZI and are useful on the east and west facades (Dev & Saifudeen, 2023). On Indore’s east facade, a fin angled approximately  $80^\circ$  from the facade blocks peak morning radiation at the AZI of  $79.86^\circ$  (Table 3) but loses effectiveness within one to two hours as the AZI shifts. It is useful as an additional device paired with horizontal louvres, but insufficient as a standalone device in any orientation.

### Rotating Facades

Rotating facades use elements that pivot on an axis and adjust to azimuth or altitude, making them highly successful in tackling variable sun paths. Their main drawback is higher maintenance complexity, especially in motorised systems (Jamilu et al., 2024).

**Figure 7: Horizontal rotating**



**Figure 8: Vertical rotating**



Horizontal Rotating (see Figure 7): Panels can rotate  $0^\circ$  to  $90^\circ$  about a horizontal pivot, based on the changing ALT throughout the day. This makes them suitable for south, south-east, and south-west

orientations in Indore, where altitude is a dominant variable. They do not respond to AZI shifts, limiting their effectiveness on east and west facades.

Vertical Rotating (see Figure 8): Panels rotate  $0^\circ$  to  $180^\circ$  about a vertical pivot, based on the AZI shifts. They are highly effective for the east and west facades of Indore, where the low HSA values during the summer solstice (Table 4) require lateral interception that no horizontal device can provide. The Al Bahr Towers in Abu Dhabi, UAE, a commonly cited example for adaptive facades, uses a climate-responsive triangular screen system that adjusts and tracks the sun's azimuth throughout the day, reducing the facade's heat gain by approximately 50% (Hosseini et al., 2019; Karanouh & Kerber, 2015).

### Folding Facades

Folding facades have panels that open and close along a hinge in a zig-zag or bi-folding manner, allowing the shaded area to be controlled as needed (Wang et al., 2022). Unlike rotating facades, these facades provide flexibility in linearly controlling the shading area.

**Figure 9: Horizontal folding**



**Figure 10: Vertical folding**



Horizontal Folding (see Figure 9): Panels are hinged on a horizontal edge, folding between a fully open and fully closed position. When closed, they act as a solid horizontal shading plane blocking high-altitude radiation on south, south-east, and south-west orientations, as seen in the Kiefer Technic Showroom, Austria (Romano et al., 2018). However, they cannot provide graduated shading, resulting in over-shading or under-shading during variable seasons.

Vertical Folding (see Figure 10): Panels are hinged on a vertical edge and fold laterally outwards to intercept radiation on east, west, north-east, and north-west orientations (Dev & Saifudeen, 2023). A panel folded to  $90^\circ$  blocks the morning radiation received by the east facade effectively, but cannot track AZI as it shifts through the day. This limits the usefulness to orientations with a defined and brief peak exposure window (Wang et al., 2022).

### Sliding Facades

Sliding Facades have panels that move along tracks to open and close portions of the facade. These facades are also area-based rather than angle-based, making them less responsive based on solar geometry (Dev & Saifudeen, 2023).

**Figure 11: Horizontal sliding**



**Figure 12: Vertical sliding**



Horizontal Sliding (see Figure 11): Panels travel along vertical tracks, displacing upward or downward to progressively cover the facade surface in response to ALT variation (Dev & Saifudeen, 2023). The system cannot address AZI-driven exposure and is therefore limited to south, south-east, and south-west orientations.

Vertical Sliding (see Figure 12): Panels travel along horizontal tracks, displacing laterally to cover the facade surface in response to AZI variation (Dev & Saifudeen, 2023). Though these facades do not track AZI, they provide partial blockage from peak morning and afternoon radiation on the east and west facades.

Table 10 represents the adaptation logic of the four typologies studied for better comparison.

**Table 10: Adaptation logic of studied facade typologies**

Typology	Sub-Type	Mode of response	Primary control variable	Key Angles of In-dore	Design Implication
Static	Horizontal (Chajja/ Louvres)	Fixed shading projection	VSA/ ALT	Summer noon ALT 89.31°, winter noon ALT 43.79°, south winter noon VSA 67.24°	Suitable for south control, but may block useful winter admission.
	Vertical (Fins)	Fixed lateral interception	HSA/ AZI	East summer 9:00 HSA -10.14°, west summer 3:00 HSA 10.14°	Useful only for a narrow exposure band on the east and west.
Rotating	Horizontal	Angular adjustment about the horizontal axis	ALT	Summer noon ALT 89.31°, winter noon ALT 43.79°	Best where seasonal change in sun height is the main issue.
	Vertical	Angular adjustment about the vertical axis	AZI	Summer 9:00 AZI 79.86°, winter 9:00 AZI 133.61°	Best for east-west low-angle exposure and shifting lateral sun.

<b>Folding</b>	Horizontal	Open-close motion by hinged panels	ALT	South noon HSA 0°, south winter noon VSA 67.24°	Useful where shading and daylight both matter.
	Vertical	Lateral fold by hinged panels	AZI	East summer 9:00 HSA -10.14°	Effective for short, defined exposure windows.
<b>Sliding</b>	Horizontal	Changes the area coverage	ALT	South summer noon ALT 89.31°, south winter noon ALT 43.79°	Good for proportional coverage, weaker for precise tracking.
	Vertical	Changes the lateral area coverage	AZI	East summer 9:00 HSA -10.14°, west summer 3:00 HSA 10.14°	Provides partial east-west shielding, but not a continuous response.

## 6. Methodology and Evaluation Matrix

The study uses a qualitative evaluation combined with a literature review, climatic analysis and typological matrix evaluation to determine suitable adaptive facade typologies for Indore. Facade typologies were selected through purposive sampling and snowballing. Latitude 22.76° N was selected for calculating solar geometry covering altitude, azimuth, shadow angles, incidence and facade radiation load across the eight major orientations. The selected typologies were then compared based on six qualitative criteria, namely, cut-off efficiency, radiation blockage, seasonal responsiveness, east-west performance, user control, and maintenance complexity, as seen in Table 11.

The first stage involved establishing the scope through purposive sampling, targeting literature directly relevant to shading devices, facade typologies and adaptive systems in climatic zones like Indore. Key papers guided a snowball search to trace recurring authors, typologies and frameworks in the adaptive facade study. Selected facade typologies were then reviewed to identify their operating principles, movement logics, control mechanisms and solar performance. Particular attention was given to solar geometry to determine the effectiveness of each facade system in intercepting solar radiation across the variable seasonal conditions and different orientations.

**Table 11: Evaluation criteria and assessment basis**

Criterion	What it assesses	Basis in this study
Cut-off efficiency	Ability to block direct incident solar radiation	ALT, HSA, VSA patterns across orientations
Relative radiation blockage	Ability to reduce solar exposure on the facade plane	INC and facade-radiation
Responsiveness to seasonal variation	Ability to adjust between summer protection and winter admission	Solstice and equinox angle change
East-west performance	Ability to control low-angle lateral radiation	AZI and HSA values on E and W facades

User control	Scope for manual or automated adjustment	Typology movement logic
Maintenance complexity	Operational and mechanical burden	Degree and type of movement

Each typology was qualitatively assessed as low, moderate, or high to keep the matrix aligned with the available studies and evidence, as seen in Table 12.

**Table 12: Comparative suitability matrix of facade typologies**

Typology	Cut-off efficiency	Radiation blockage	Seasonal responsiveness	East-west performance	User control	Maintenance complexity
Static	Moderate	Moderate	Low	Low to moderate	Low	Low
Rotating	High	High	High	High	High	High
Folding	High	Moderate to high	Moderate to high	Moderate to high	Moderate	Moderate
Sliding	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate

## 7. Results

The default, static facades tend to perform better in orientations they are designed for, especially on south facades, but fail to perform in seasonal changes and low-angle radiation. Adaptive facades, due to their high adaptivity, perform better than static facades in Indore’s variable solar conditions. Among these, rotating facades display the highest adaptability, followed by folding and then sliding.

The main advantage of rotating facades lies in their ability to respond directly to the changing solar angle based on the orientation they’re designed for. This makes them superior in Indore than other typologies, as different orientations require different angles to cater to. South orientation, for example, requires altitude-based control, while east and west require azimuth-based interception for low-angled radiation.

Folding facades rank second due to their adaptability in controlling the opening despite lacking solar tracking capabilities. Sliding facades remain suitable only in selected conditions due to their proportional coverage being the primary operation rather than solar angle-based adaptivity. They are the least suitable among adaptive facades for variable solar conditions.

The orientation-based results guide the identification of the most suitable facade typology for each of the eight studied orientations in Indore. The final findings are presented in Table 13 through a suitability matrix derived by the combination of solar angle analysis and typological comparison.

**Table 13: Orientation-based typology suitability in Indore**

Orientation	Primary solar issue	Recommended typology	Reason
North	Limited direct exposure, low control demand	Static or sliding	Minimal direct solar stress and limited need for active angular response
North-East	Morning low-angle radiation	Vertical rotating or vertical folding	Requires azimuth-responsive lateral interception

East	Strong morning glare and heat gain	Vertical rotating	Best suited to low-angle lateral solar control
South-East	Mixed morning and high-altitude exposure	Rotating or folding	Requires combined directional and seasonal response
South	High-altitude solar load with winter admission need	Horizontal rotating or horizontal folding	Best suited to altitude-based cut-off with adaptable openness
South-West	Afternoon heat and mixed exposure	Rotating or folding	Requires variable response throughout the day
West	Strong afternoon glare and heat gain	Vertical rotating	Best suited to low-angle lateral interception
North-West	Late-day low-angle exposure	Vertical rotating or vertical folding	Requires azimuth response and controlled lateral closure

Based on the suitability matrix, a clear pattern is observed with the south orientation dictated by the altitude, thus making horizontal rotating and folding strategies the most suitable, east and west dominated by the azimuth and characterised with low-angle radiation, making vertical rotating the most viable, while the south-east and south-west require a mixed strategy. Thus, rotating and folding facade typologies tend to outperform static and sliding typologies.

## 8. Conclusion

This study analysed four facade typologies for reducing solar radiation in Indore. It concludes that static facades are insufficient for the composite climatic zones as the variable solar angles across different seasons and orientations demand adaptive systems that can respond to the changing altitudes and azimuth throughout the year.

Among the facade typologies studied, rotating facade systems were the most suitable, followed by folding systems, while the sliding systems were suitable for selected conditions only. The orientation-based suitability matrix provides a starting point for facade selection at the early design stage.

The study contributes a solar geometry-based framework for the selection of facades in composite climates, supporting a reduce-before-produce and climate-responsive design approach to building performance.

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