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Original Article

DESIGNING KINETIC FAÇADE FOR AN OFFICE BUILDING IN WARM AND HUMID CLIMATE TO IMPROVE THE DAYLIGHT QUALITY – AN INTEGRATED COMPUTATIONAL APPROACH

Sakshi Birkad [1], **Amitava Sarkar** [1]
[1] Department of Architecture, School of Planning and Architecture, Vijayawada, Andhra Pradesh, India

ABSTRACT

Daylighting plays a crucial role in providing comfort within buildings, as occupants have a strong preference for well-lit spaces that reduce reliance on artificial lighting. Considering growing concerns surrounding energy efficiency and sustainability, daylighting design has gained significance beyond its aesthetic and psychological implications. The building facade serves as a key element for controlling the penetration of natural light into indoor spaces. In this regard, a climate-based approach and the observation of dynamic sky conditions offer effective methodologies for this study. Kinetic architecture, inspired by nature and intricate geometries, integrates form and technology. In the context of enhancing visual comfort, daylight performance, and reducing glare, the implementation of innovative daylighting guide systems with real-time control through kinetic configurations becomes imperative. This study aims to propose a systemic computational approach to design a tri-fold kinetic facade configuration tailored for office buildings in warm and humid climates, aligning with specific daylighting design criteria. The research methodology deploys both the qualitative approach, through the assessment of feedback from the users regarding the visual comfort, and the quantitative approach, through the assessment of onsite measurement of visual environment in the office space and also by using the building simulation tools to calculate the various parameters related to the indoor visual environment affecting the performance of the office activity. The results from the analysis have shown that, when compared with the absence of any such kinetic façade, the proposed tri-fold kinetic facade can improve the visual and daylight performance of a building by reducing the annual sunlight exposure by 73-90% and annual disturbing glare by 73-91% which is significant to create cooling effect indoor. Optimal opening angles of the proposed kinetic façade for different orientations are also calculated regarding the different seasonal representative days. Limitations of the present study and the scope of further research are also highlighted.

Keywords: Kinetic Facade, Daylight Optimization, Office Building, Warm-Humid Climate, Simulation Analysis, Computational Approach

INTRODUCTION

BACKGROUND AND NEED FOR THE STUDY

The design of the building envelope is a crucial factor in determining the indoor physical environment, specifically in terms of thermal and visual comfort Wang et al. (2012). To promote the well-being of occupants, it is essential to provide sufficient natural

*Corresponding Author:
Email address: Amitava Sarkar (amitava.sarkar3@gmail.com)

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light, which has positive effects on their physical, psychological, and mental health, and is considered a renewable and permanent source Hosseini et al. (2021). Innovative building envelopes incorporate dynamic components that respond to changing climatic conditions to enhance daylight performance and visual comfort.

Kinetic architecture is a design approach that combines form and technology, drawing inspiration from nature and geometric complexity in building structures. A kinetic façade is an automatic and responsive design that features dynamic elements capable of various movement such as flap, fold, rotate, slide, scale, expand, extract, and change in response to daylight Ahmed et al. (2015), Carlucci (2021). This adaptive feature enhances the occupant's visual comfort by integrating with its peripheral environment using sensors and actuators. The primary criterion for office lighting is to offer sufficient illumination for a visual activity such as working/ reading.

Visual comfort is the most dominant factor in human perception since the eye contains two third of nerve fiber within human central nervous system. The mental and psychological state of individuals can be influenced by the level of visual comfort they experience International Organization for Standardization. (2025). Workplaces and study environments, such as offices or production spaces, can benefit from a comfortable lighting environment, which can elevate mood and enhance work efficiency Tabadkani et al. (2018), Tabadkani et al. (2019). Consequently, there has been a growing demand for visual comfort from building occupants. As the thought of comfort has evolved, one approach to enhancing visual comfort and enhancing occupant productivity is through the motion of changing façade configurations. Three-dimensional alterations in the façade elements can control microclimate forces such as wind and solar energy, thus improving the level of visual comfort and productivity Hosseini et al. (2019).

Since past 20 years, there is a revolutionary change in building and construction technology along with the development in the information technology (IT) sector which can be seen in the new constructions which deploy many attractive envelopes many a time forgetting the conditions inside which can lead to visual discomfort that in turn may cause ill health to the occupants and reduction in the productivity. If the parameters of visual comfort are not integrated in the design phase, such buildings may consume more energy for lighting and cooling loads.

As per the information U.S. (2021), India stands in the 3rd largest energy consumer. The building sector in India contributes to about 35% of total electricity consumption BEE, (2017). Building envelope/ facades are the most important contributors to allow large amounts of daylight which influences the comfort factors within the buildings and energy efficiency of the buildings.

The main reason in the consideration of office building for this study is that they function mostly in the daytime where the most useful naturally available daylight can be utilized to optimize the need for artificial lighting which consumes more energy. Hence, there is a necessity to apply the effective strategies to reduce the effects of visual discomfort due to less availability of daylight during the working hours in the office building.

AIM, OBJECTIVES, SCOPE AND LIMITATIONS

The aim of the present research is to design the kinetic façade for an office building with regards to daylight quality in warm and humid climate of Vijayawada to improve its visual comfort through a systemic computational approach which can be applied in other similar conditions. To fulfill the aim, the objectives of the research include – (a) to propose the methodology for a systemic computational approach to design adaptive kinetic façade for optimal visual performance; (b) to study the parameters for evaluating indoor visual comfort; (c) to assess the climatic context and design kinetic façade for improved visual comfort; (d) to evaluate the performance of designed kinetic façade for the optimal daylight quality; and (e) to determine the optimal angle of façade unit for specific months on different timings.

Scope

Parameters like orientation, kinetic façade transformation system, angle of façade unit, material type, etc. are taken into consideration in this study. The study of controlled daylight distribution, the availability of daylight, glare and view factor are considered. The study has assessed the parameters of visual and daylight performance such as Useful Daylight Illuminance (UDI), Spatial Daylight Autonomy (sDA), Annual Sunlight Exposure (ASE), and Glare.

Limitations

Due to time constraints the major focus is given on improving the visual comfort and daylight performance for an office building in warm and humid climate. This can be further extended to carry out the thermal and energy performance of the building. Cost and maintenance aspect is not taken into consideration in the present study.

Research Questions

The present research also attempts to find answers to the following research questions relevant to the scope of the study: (i) What strategies can be employed to improve daylight distribution in buildings in a warm and humid climate? (ii) Can a kinetic facade be considered as a viable solution to enhance visual comfort in the warm and humid climate of Vijayawada? (iii) What is the process for selecting the appropriate kinetic façade among the various options? (iv) How can the distribution of indoor daylight be optimized during the design of the kinetic facade?

REVIEW OF LITERATURE

VISUAL COMFORT

Natural light has many positive effects on health and energy efficiency, but it also comes with certain challenges. For example, heat gains and visual discomfort in the form of daylight glare must be considered to ensure visual comfort. Balancing visual comfort with daylight presents a complex undertaking, necessitating a comprehensive comprehension of the interplay between human requirements and lighting conditions. Crucial factors such as light quantity, uniformity, color rendering quality, and glare risks for occupants must be meticulously taken into account International Organization for Standardization. (2025). Parametric simulations can provide data on these factors to facilitate an accurate and efficient evaluation of daylight performance Rizi and Eltaweel (2021).

PARAMETERS FOR EVALUATING VISUAL COMFORT

Many researches on the effect of daylighting in buildings have identified several performance factors that contribute to the improvement of visual comfort in a building Elghandour et al. (2016), Hosseini et al. (2019a), Tabadkani et al. (2019). As per the literature, the following factors are essential to provide visual comfort to the occupants in a space: (a) Daylight Availability (or Distribution) - Task Illuminance and Uniformity; (b) Glare - caused by the brightness of the source or the relative luminance of the room surfaces; (c) Task-Surface Contrast - The distinction between the task and its surrounding surface; (d) View - The aesthetic appeal and visual quality of the image.

STUDY OF DAYLIGHT METRICS AND STANDARDS

The study's objectives focus on assessing and improving the visual comfort in an office space by optimizing the proposed adaptive kinetic façade through integrated design and computational approach. The metrics and standards identified based on the literature review Illuminating Engineering Society. (2012), U.S. (2015) , Elghandour et al. (2016), BEE, (2017), Mekhamar and Hussein (2021), Hosseini et al. (2021), Natiq and Abdulqader, (2023), International Organization for Standardization. (2025) to do the analysis for this purpose are discussed in the following sections.

SPATIAL DAYLIGHT AUTONOMY (SDA):

The Illuminating Engineering Society (IES) has developed guidelines for testing and calculating two important climate-based daylight metrics - Spatial Daylight Autonomy and Annual Sunlight Exposure Illuminating Engineering Society. (2012). These metrics are commonly used for evaluating daylight performance and have also been incorporated into building certification systems such as Leadership in Energy and Environmental Design (LEED) U.S. (2015) .

The percentage of a space that is illuminated with a lighting level of at least 300 lux for at least half of the occupied hours during the year (from am to pm) on the horizontal work plane positioned 30 inches above the floor. To meet the requirement, a minimum of 55% of the floor area must achieve this threshold U.S. (2015) .

ANNUAL SUNLIGHT EXPOSURE (ASE)

The percentage of a space that is exposed to direct sunlight with an illuminance level of 1000 lux or higher for at least 250 hours during the occupied period each year, leading to discomfort and glare Illuminating Engineering Society. (2012). This metric is particularly relevant when the space is unobstructed, and glare control is required using shading devices. The ASE should not exceed 10% of the floor area, and this metric is useful for identifying when shading is necessary in indoor spaces, allowing for the design of appropriate shading systems Illuminating Engineering Society. (2012). LEED V4 recommends that the ASE be limited to no more than 10%, making it the second optimization goal USGBC (2013).

USEFUL DAYLIGHT ILLUMINANCE (UDI)

This refers to the fraction of time throughout the year during which the indoor horizontal illuminance from daylight, measured at a particular point, meets a specific threshold in each area Reinhart and Wienold (2011), Wagdy and Fathy (2015). The three ranges of the UDI for office spaces are: UDI underlit = <300 lux; UDI useful = 300 – 2000 lux; and UDI over-lit = >2000 lux. As per the Energy Conservation Building Code of India (ECBC), 50% of the floor area above ground should fulfil the above criteria for office buildings BEE, (2017).

DAYLIGHT GLARE PROBABILITY (DGP)

This metric represents the proportion of individuals who are affected by discomfort glare. It is a novel technique for predicting glare, which is based on empirical observations of the vertical eye illuminance (Ev) instead of the background luminance (Lb) Wienold and Christoffersen (2006). The four ranges of the DGP for office spaces are given in Table 1 below.

Table 1

Table 1 Daylight Glare Probability (DGP) Index.

DGP Rating	Lower limit	Upper limit
Imperceptible glare	0	35%
Perceptible glare	35%	40%
Disturbing glare	40%	45%
Intolerable glare	45%	-

Source: Garcia and Pereira (2019)

RELEVANCE TO SUSTAINABILITY

Visual comfort and natural daylight are the crucial aspect in office building to improve the occupant's productivity. Using natural light efficiently can have numerous benefits for both physical and mental health of workers, such as reducing visual fatigue and improving work efficiency while also lowering energy consumption. Several noteworthy building projects located different parts of the world with hot-humid climatic conditions such as - Simons Centre at Stony Brook, New York, USA (2008), Media ICT building, Barcelona, Spain (2011), Al Bahr Towers, Abu Dhabi, UAE (2013), Helio Trace Façade System, New York, USA (2013), SDU University of Southern Denmark, Denmark (2014), etc. have shown that by being responsive to changing climatic conditions, kinetic facades can improve daylight performance, energy performance and enhance visual comfort using adaptive and interactive mechanisms Razoki and Al-Kazzaz (2025). Following are some of the benefits of design for daylighting observed from the literature review: (a) Health benefit – Access to natural views reduces stress and such improved vision helps to work for longer time Tabadkani et al. (2019), Day et al. (2019), (b) Energy efficiency – Optimization of daylighting design can save up to 15-40% of total annual building energy consumption. It can also cut the energy usage of building lighting by 75-80% at times Elghandour et al. (2016), Garcia and Pereira (2019); and (c) Financial benefit - Studies have found that people can perform 10-25% better in daylit space rather than in a dimly-lit room Rizi and Eltaweel (2021), Hosseini et al. (2021).

MATERIALS AND METHODS

RESEARCH METHODOLOGY

Researchers Elghandour et al. (2016), Waseef and Nashaat (2017), Mekhamar and Hussein (2021), Tabadkani et al. (2021), Natiq and Abdulqader (2023) have highlighted the benefit of designing dynamic climate responsive kinetic façade for visual and thermal comfort utilizing the qualitative and quantitative simulation tools. The present research deploys combination of both qualitative and quantitative research methods. The activity flowchart followed in the present research process is shown in Figure 1 and the flowchart of the working process of design optimization analysis through simulation tools is shown in Figure 2.

The proposed flowcharts signify a systemic novel computational approach by integrating the different stages of the design development along with the façade optimization process dynamically and harmoniously in sync to the local context with the help of building simulation tools. This proposed computational approach can be furthered to develop an artificial intelligence (AI) based algorithm incorporating machine learning (ML) to process 'big data' to design adaptive kinetic façade as per local geo-climatic condition and building usage.

Figure 1

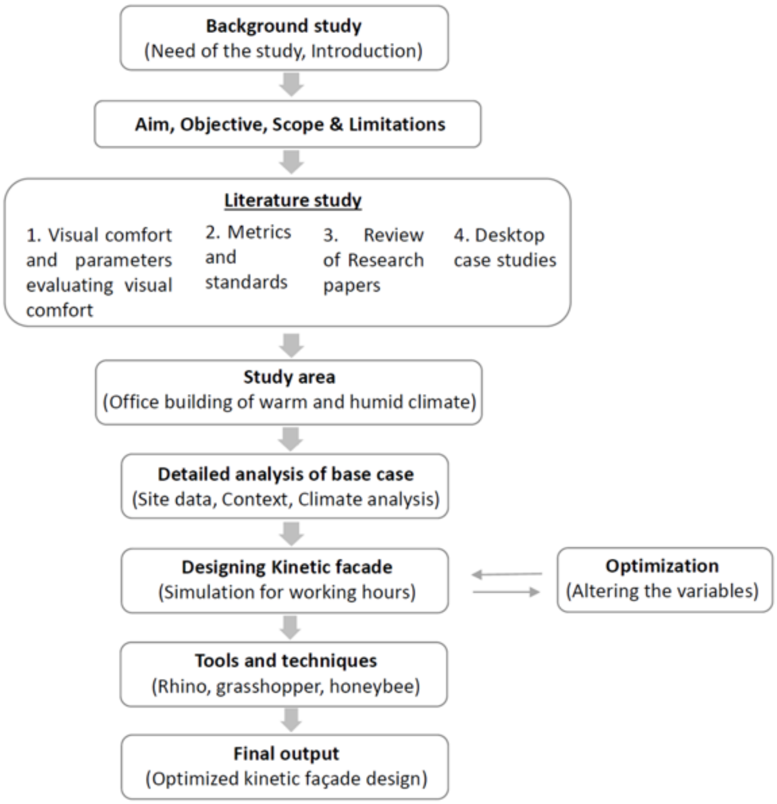

Figure 1 Flowchart Showing the Research Methodology.
Source: Authors

Figure 2

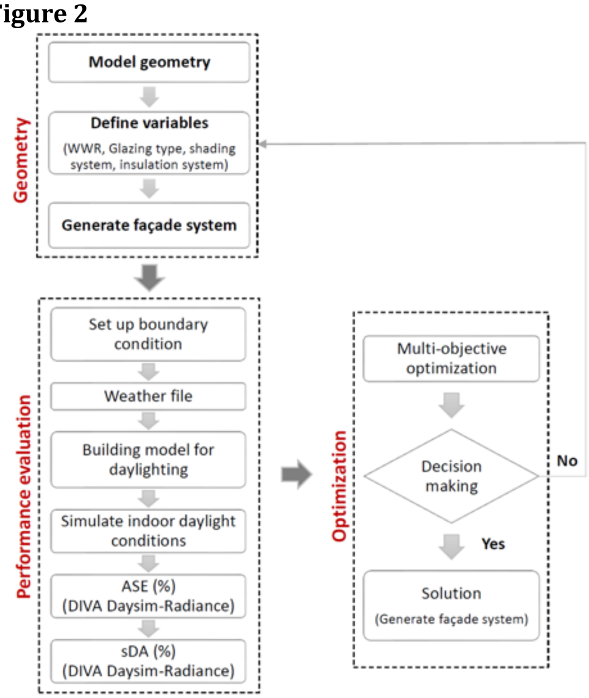

Figure 2 Flowchart Showing the Working Process of Design Optimization Analysis.
Source: Authors

STUDY AREA AND CLIMATE ANALYSIS

The selected commercial office building site is situated in Enikepadu, Vijayawada, Andhra Pradesh (A.P.), India (16.53° N Latitude, 80.797° E Longitude, Altitude 29.25m above MSL) and is connected to 90' wide road on southern side. Vijayawada has 28.2°C as mean annual temperature, with May and June being the hottest month having average temperature of 33.5°C, and December being the coolest month at 24.2°C on average. The total annual rainfall is 974 mm, with the driest month being January at 6 mm and the wettest being August at an average of 179 mm India Meteorological Department. (2022) .

For the analysis of Vijayawada climatic data, digital climate file IND_AP_Gannavaram-Vijayawada.AP.431810_TMYx.epw (WMO_Region_2_Asia) has been used. From the analysis of the solar radiation data of Vijayawada, it is observed that the north facade receives the lowest radiation. The south and west wall receives the maximum radiation from the afternoon sun and thus this facade has the most heat gain (see Figure 3). Hence, high performance glazing can be provided on all surfaces for reducing heat gain in the summer and south, west and east wall openings should be shaded effectively to avoid the maximum solar radiation.

Figure 3

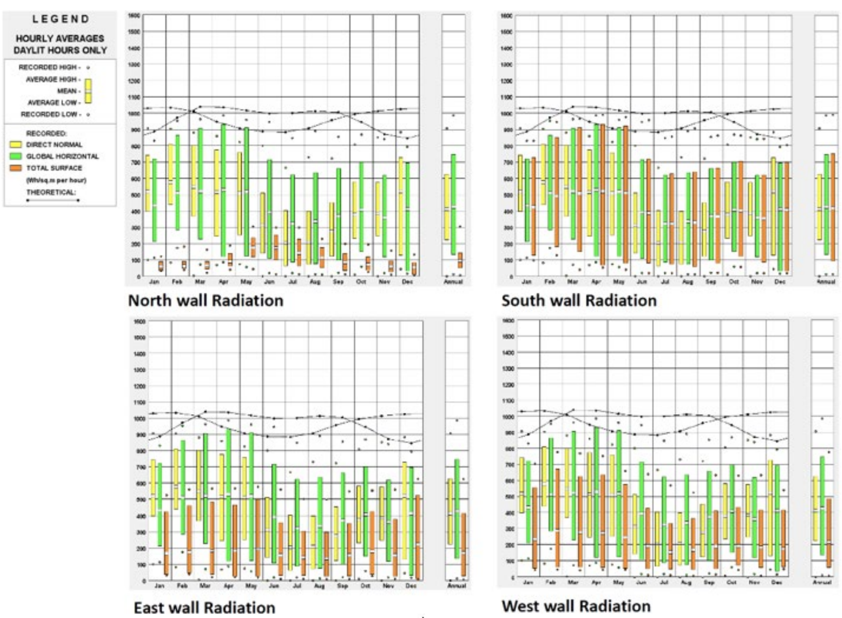

Figure 3 Graphs Showing Radiation Range.
Source: Authors and Climate Consultant Tool

Further, form the analysis of the sky-cover data it is found that from July to November, the mean cloud cover is increased hugely from the average mean percentage which indicates the highest amount of diffuse solar radiation to the earth surface. The direct solar radiation is higher from December to June due to the minimum sky cover which results in intense solar radiation. The annual sky cover ranges from 21 to 89%.

Also, it is observed from the sky illumination data that the illumination range is high in the summer months with a maximum of 95000 lux. Therefore, indoor comfort level should be maintained with adequate shading on openings and on exposed surfaces. Also, effective shading is required to dissipate radiation and heat gain.

DETAILS OF THE SELECTED OFFICE BUILDING

The building site is encompassed by commercial properties on the east, west, and south sides, while residential spaces border the northern side. Building's front façade is facing towards south-west direction. It is curtain-glazed from top to bottom. The site location and site context are shown in Figure 4. The selected office building has a site area of 544.8 m2 and total built-up area of 6,405 m2 spread over G+7 floors with 2 basement parking. Total height of the building above ground is 28.8m and floor to floor height is 3.6m. Surrounding areas include residential buildings, commercial shops, hospitals, ATM and open spaces. The views of the selected office building are shown in Figure 5. The surface area/ volume ratio is calculated as 3821/14475.6 = 0.26, which is compact. The occupancy capacity is 100-150 persons in each floor. The floor plans and elevations of the selected office building are shown in Figure 6.

Figure 4

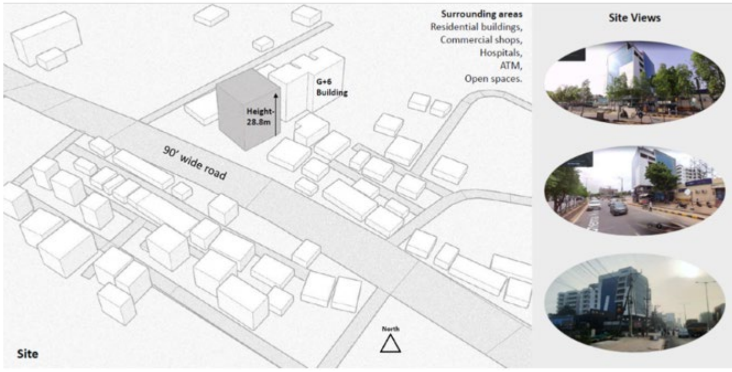

Figure 4 Site Details and Site Context of the Selected Office Building.
Source: Authors

Figure 5

Figure 5 Views of the Selected Office Building.
Source: Authors

Figure 6

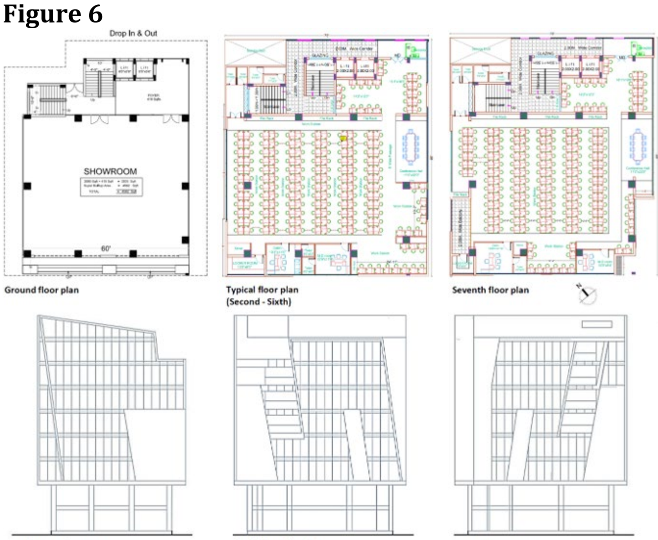

Figure 6 Floor Plans and Elevations of the Selected Office Building.
Source: Authors

The researchers Day et al. (2019) have highlighted that useful insights can be obtained by conducting the on-site questionnaire survey regarding visual comfort with the occupants. Hence, in the present study, the visual comfort questionnaire survey is conducted, as per the International Organization for Standardization. (2025). guidelines, with the users who uses office for daytime working. Aspects covered in the on-site questionnaire survey are comfort factors, user preferences in the office, artificial lighting needs and discomfort experienced by existing openings, while making observations as well. The sample visual comfort questionnaire is given in Annexure-1. The findings are discussed in the following sections.

SIMULATION MODEL AND VALIDATION

In the present study simulation tools used for the visual performance analysis include Rhino and Grasshopper (Ladybug and Honeybee plug-ins). Further, Honeybee for Rhino is used for the daylight simulations with Radiance and Daysim. The details of the baseline simulation model of the selected office building developed in Rhino is shown in Figure 7 (d)and(e).

Figure7

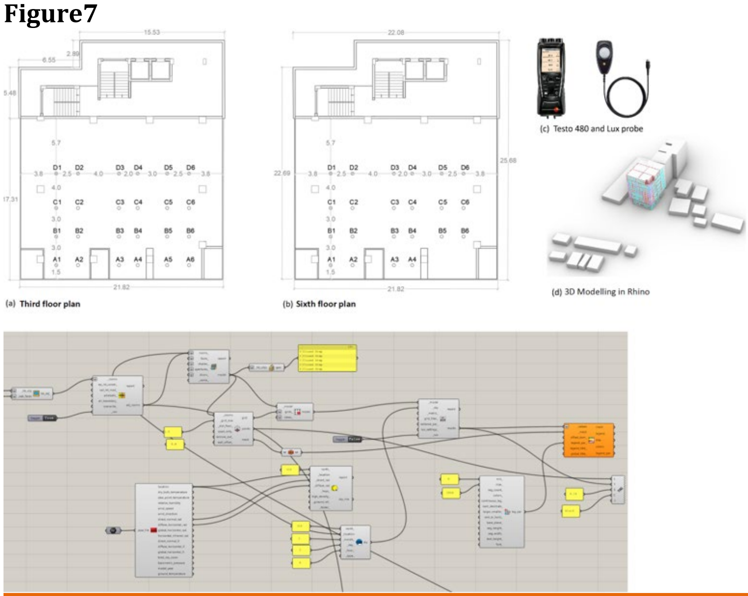

Figure 7 Details Regarding Daylight Analysis of the Selected Office Building.
Source: Authors

To validate the simulation analysis, on-site measurement of illumination level is done by using the Lux meter (Testo 480) and Lux Probe (see Figure 7(c)) in the third floor (see Figure 7(a)) and sixth floor (see Figure 7(b)) of the office building during March 2 and 3, 2024. The sky condition is clear sky with sun. The on-site measured lux values are given in Table 2 to Table 5.

Table 2

Table 2 Measurement of Light Intensity (Lux) in Third Floor Office Space on 2nd Feb 2024.

Measur-ment points Time	A1	A2	A3	A4	A5	A6	B1	B2	B3	B4	B5	B6	C1	C2	C3	C4	C5	C6	D1	D2	D3	D4	D5	D6
8:00 AM	572	243	585	218	487	492	161	131	111	165	315	854	154	105	144	167	291	1077	160	115	110	269	400	605
10:00 AM	1200	460	641	362	640	745	298	297	198	239	327	731	238	200	185	208	354	556	108	161	108	161	210	306

12:00 PM	569	665	614	527	530	606	372	376	246	294	394	564	380	230	174	198	255	416	128	172	102	140	159	292
2:00 PM	544	617	548	541	553	675	477	460	221	310	319	528	432	384	192	189	281	299	247	197	129	145	155	154
4:00 PM	420	593	337	412	413	538	406	349	206	254	255	498	965	410	265	153	145	248	444	396	280	137	118	127
6:00 PM	8	12	7	10	8	9	7	4	2	3	3	3	4	2	3	2	3	6	6	5	4	3	3	5

Table 3

Table 3 Measurement of Light Intensity (Lux) in Sixth Floor Office Space on 2nd Feb 2024.

Measure-ment points Time	A1	A2	A3	A4	B1	B2	B3	B4	B5	B6	C1	C2	C3	C4	C5	C6	D1	D2	D3	D4	D5	D6
8:00 AM	849	364	472	426	130	120	109	134	197	238	69	68	70	111	209	596	119	85	120	289	560	[illegible]
10:00 AM	825	700	833	702	167	160	159	180	165	326	111	126	108	108	192	276	168	117	65	174	225	[illegible]
12:00 PM	761	870	635	1061	207	229	187	219	106	307	287	135	112	98	100	131	223	125	50	73	105	[illegible]
2:00 PM	623	902	524	1442	225	251	178	198	98	252	317	153	110	94	98	159	584	219	107	63	94	[illegible]
4:00 PM	610	890	422	1439	168	212	152	209	69	107	416	214	120	90	66	108	624	448	195	58	85	[illegible]
6:00 PM	19	19	20	34	13	5	3	3	3	5	15	3	2	2	3	4	4	3	4	2	3	[illegible]

Table 4

Table 4 Measurement of Light Intensity (Lux) in Third Floor Office Space on 3rd Feb 2024.

Measure-ment points Time	A1	A2	A3	A4	A5	A6	B1	B2	B3	B4	B5	B6	C1	C2	C3	C4	C5	C6	D1	D2	D3	D4	D5	D6
8:00 AM	552	240	575	218	477	491	159	130	113	175	311	864	154	105	154	177	281	1087	168	115	110	259	408	598
10:00 AM	1200	470	638	362	630	725	298	287	197	235	324	730	248	200	188	208	354	556	108	159	108	166	212	309
12:00 PM	559	663	614	527	530	606	370	376	249	294	392	574	380	233	178	202	251	418	123	170	101	142	159	290
2:00 PM	534	618	538	540	551	675	475	460	223	300	319	528	432	374	192	189	280	301	247	194	132	145	151	151
4:00 PM	410	583	337	411	403	528	403	347	216	254	259	498	975	407	255	150	141	253	454	396	286	147	119	122
6:00 PM	8	12	7	10	8	9	7	4	2	3	3	3	4	2	3	2	3	6	6	5	4	3	3	5

Table 5

Table 5 Measurement of Light Intensity (Lux) in Sixth Floor Office Space on 3rd Feb 2024.

Measure-ment points Time	A1	A2	A3	A4	B1	B2	B3	B4	B5	B6	C1	C2	C3	C4	C5	C6	D1	D2	D3	D4	D5	D6

8:00 AM	844	360	462	423	127	115	109	137	197	238	72	68	73	115	209	626	119	82	130	293	570	636
10:00 AM	820	700	830	699	167	158	159	176	161	328	111	128	109	106	192	276	166	117	65	177	235	299
12:00 PM	761	867	631	1051	209	227	185	215	102	307	287	132	110	99	102	136	220	125	50	70	105	232
2:00 PM	629	901	524	1442	225	252	179	198	102	252	327	153	114	96	94	159	588	219	117	61	96	203
4:00 PM	610	888	422	1429	172	215	155	209	75	107	414	210	120	90	69	106	621	453	195	52	82	87
6:00 PM	19	19	20	34	13	5	3	3	3	5	15	3	2	2	3	4	4	3	4	2	3	5

Further, the lux values are calculated for the same dates, same time-intervals, same sky condition and same floors with the Rhino. The calculated values are shown in Table 6 to Table 9. To assess the consistency between the measured values and calculated values Pearson's Correlation statistical analysis is done. In statistics, correlation refers to the degree of linear association between two variables. A correlation coefficient is employed to gauge the extent of the association between these variables, with values ranging from -1 to 1. When the magnitude of a correlation coefficient falls between 0.9 and 1.0, it indicates a high degree of correlation between the variables. Similarly, a coefficient falling between 0.7 and 0.9 is indicative of a strong correlation, while one between 0.5 and 0.7 is considered moderate. Correlation coefficients ranging from 0.3 to 0.5 are generally considered low. In the present study correlation coefficient ranges from 0.63 - 0.75 which shows high level of correlation. Hence, further study is carried out using the same simulation tools.

Table 6.

Table 6 Calculated Light Intensity (Lux) in Third Floor Office Space on 2nd Feb 2024.

Measure-ment points Time	A1	A2	A3	A4	A5	A6	B1	B2	B3	B4	B5	B6	C1	C2	C3	C4	C5	C6	D1	D2	D3	D4	D5	D6
8:00 AM	2853	1138	1956	1229	2158	1249	739	575	520	698	1069	1417	635	458	464	752	1236	1639	586	410	482	888	1225	1516
10:00 AM	1992	1928	2402	1893	2841	2648	1253	937	779	924	1297	1731	1075	704	601	702	1087	1975	1010	578	467	571	1022	2153
12:00 PM	2767	2306	2010	2218	2428	2332	1399	1100	778	974	1194	1460	1283	800	619	662	864	1318	1220	654	466	472	693	1279
2:00 PM	2355	2551	1630	2495	2124	2551	1571	1202	772	970	1082	1393	1750	960	674	643	806	1161	1834	898	528	479	622	1097
4:00 PM	1666	2370	1230	2387	1435	2261	1633	1181	699	751	764	1011	1666	1320	752	586	596	815	9021	1462	726	480	475	777
6:00 PM	418	619	334	563	388	638	372	264	180	202	206	290	610	409	323	187	205	271	728	547	476	412	410	486

Table 7

Table 7 Calculated Light Intensity (Lux) in Sixth Floor Office Space on 2nd Feb 2024.

Measure-ment points Time	A1	A2	A3	A4	B1	B2	B3	B4	B5	B6	C1	C2	C3	C4	C5	C6	D1	D2	D3	D4	D5	D6
8:00 AM	2736	1089	1871	1198	613	511	468	550	478	593	578	412	427	597	930	1336	495	362	457	829	1198	1924
10:00 AM	2894	1798	2385	1865	1028	845	696	754	513	747	989	622	511	555	768	1617	825	468	382	480	908	2058
12:00 PM	2493	2189	2015	2197	1127	977	714	802	412	548	1145	698	539	494	552	1005	998	525	369	386	574	1182
2:00 PM	2080	2416	1603	2455	1194	1041	665	765	379	504	1506	817	555	485	512	876	1512	691	417	361	516	990
4:00 PM	1438	2194	1212	2369	1088	939	557	585	269	359	1986	1053	597	406	387	614	1983	1201	577	355	412	690
6:00 PM	370	553	332	552	224	197	135	164	88	128	512	322	164	132	146	225	541	369	357	344	391	483

Table 8

Table 8 Calculated Light Intensity (Lux) in Third Floor Office Space on 3rd Feb 2024.

Measure-ment points Time	A1	A2	A3	A4	A5	A6	B1	B2	B3	B4	B5	B6	C1	C2	C3	C4	C5	C6	D1	D2	D3	D4	D5	D6
8:00 AM	2814	1127	1894	1223	2128	1246	730	567	526	710	1069	1417	635	458	464	752	1236	1639	586	410	482	888	1225	1516
10:00 AM	1979	1901	2356	1873	2606	2016	1251	949	762	916	1297	1731	1075	704	601	702	1087	1975	1010	578	467	571	1022	2153
12:00 PM	2746	2301	2011	2213	2417	2321	1400	1098	783	977	1194	1460	1283	800	619	662	864	1318	1220	654	466	472	693	1279
2:00 PM	2340	2545	1616	2482	2116	2521	1568	1199	776	956	1082	1393	1750	960	674	643	806	1161	1834	898	528	479	622	1097
4:00 PM	1645	2339	1221	2374	1314	1994	1627	1178	720	750	764	1011	1966	1320	752	586	596	815	1021	1462	726	480	475	777
6:00 PM	417	610	328	556	388	623	369	265	176	191	206	290	610	409	323	187	205	271	728	547	476	412	410	486

Table 9

Table 9 Calculated Light Intensity (Lux) in Sixth Floor Office Space on 3rd Feb 2024.

Measure-ment points Time	A1	A2	A3	A4	B1	B2	B3	B4	B5	B6	C1	C2	C3	C4	C5	C6	D1	D2	D3	D4	D5	D6
8:00 AM	2700	1076	1837	1195	604	498	469	566	477	593	583	413	435	607	933	1461	494	353	480	838	1275	2032
10:00 AM	2865	1783	2349	1842	1026	836	692	735	505	759	980	625	504	543	778	1619	823	462	383	491	929	2070
12:00 PM	2495	2163	2000	2188	1138	981	703	795	405	547	1144	693	523	501	565	1014	1009	525	365	378	579	1185
2:00 PM	2061	2409	1606	2452	1196	1035	669	766	386	504	1521	815	556	493	525	871	1542	699	440	374	522	1016
4:00 PM	1437	2180	1208	2345	1095	942	561	583	283	356	1974	1035	595	406	395	611	1970	1218	574	384	408	700
6:00 PM	368	552	328	549	225	195	141	151	93	125	548	343	170	145	150	227	552	378	354	385	414	507

RESULTS AND DISCUSSIONS

For time and physical constraint and easier understanding visual performance simulation analysis has been conducted for the four crucial dates - 21st March (equinox), 21st June (summer solstice), 21st September (equinox), and 21st December (winter solstice) of the year, representing summer, monsoon, and winter conditions in Vijayawada. For the more critical and finer selection of kinetic façade, daylight performance simulation analysis may be conducted for each month of a year. The findings from the analysis are synthetized and discussed in the following sections.

SUN-PATH AND SHADOW ANALYSIS

The site is exposed to the direct sun which results in direct heat gain. So proper shading devices can help in reducing direct heat gain. Regarding the building site, 3D sun-path for summer solstice (for 21st June - Time: 12:00 pm, Azimuth angle: 15.93°, Altitude angle: 82.81°, Daylight hours: 13.07 Hrs.) and winter solstice (for 21st December - Time: 12:00 pm, Azimuth angle: 178.38°, Altitude angle: 50.03°, Daylight hours: 11.09 Hrs.) are shown in Figure 8. Further, shadow analysis of the office building facades for a representative hot summer (21st March) day is shown in Figure 9. It can be observed from the shadow analysis that north-east façade is subjected to the solar radiation from 7am to 11am in the morning; north-west façade is subjected to the solar radiation from 1pm to 6pm; south-east façade is subjected to the solar radiation from 7am to 1pm; and south-west façade is subjected to the solar radiation from 11am to 6pm. Hence, south-west, south-east and north-west façades of the building should be shaded to reduce the solar heat gain. The solar altitude angle values for the selected site location in Vijayawada during different season are shown in Table 10.

Figure 8

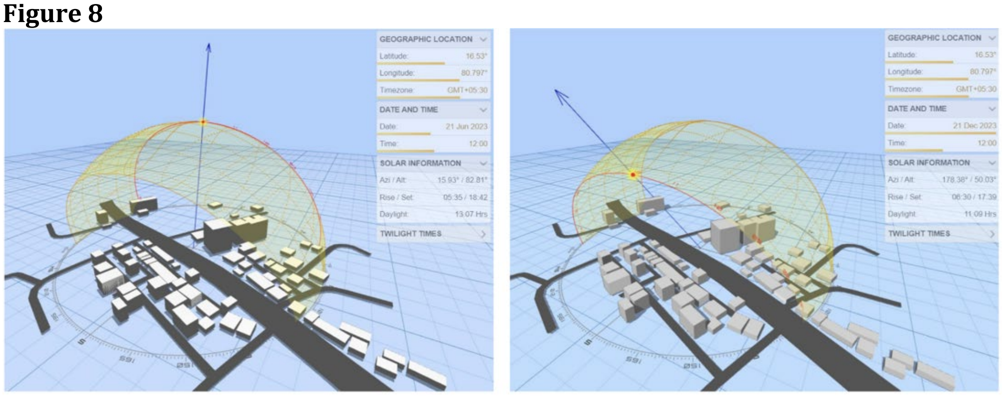

Figure 8 3D Sun-Path for Summer and Winter Solstice.
Source: Authors and Andrew Marsh tool

Figure 9

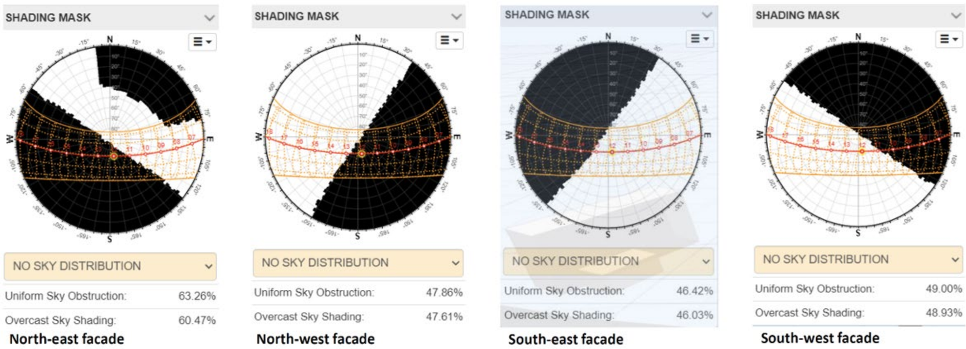

Figure 9 Shadow Analysis of the Office Building Facades.
Source: Authors and Andrew Marsh tool

Table 10

Table 10 Sun Angles for the Selected Site Location in Vijayawada.
Source: Andrew Marsh Tool

Location	Enikepadu, Vijayawada, Andhra Pradesh (16.53° N Lat., 80.797° E Long.)			
Time	**Solar Altitude Angles**			
	Spring Equinox 21st March	**Summer Solstice 21st June**	**Autumn Equinox 21st September**	**Winter Solstice 21st December**
7.00 am	18.09°	24.73°	21.78°	11.98°
8.00 am	32.31°	38.41°	35.98°	24.09°
9.00 am	46.25°	52.16°	49.85°	35.01°
10.00 am	59.44°	65.79°	62.82°	43.83°
11.00 am	70.26°	78.54°	72.63°	49.17°
12.00 pm	73.21°	81.49°	72.65°	49.60°
1.00 pm	65.28°	69.76°	62.86°	44.98°
2.00 pm	52.89°	56.24°	49.90°	36.61°
3.00 pm	39.23°	42.49°	36.03°	25.96°
4.00 pm	25.12°	28.78°	21.83°	14°
5.00 pm	10.85°	15.23°	7.56°	1.51°
6.00 pm	-3.52°	2.14°	-6.89°	-12.06°

VISUAL COMFORT QUESTIONNAIRE SURVEY OF OFFICE STAFF

The study involved field-survey for gathering data through observations and distributing questionnaires to individuals who utilize the office during the daytime for work purposes. In total, 44 (20 male and 24 female) responses are taken at the site. The analysis of the responses of the visual comfort questionnaire survey are shown in Figure 10. The questionnaire is shared with the users of the office building as a google form as well as hard copies.

It is found from the analysis that users with east orientation desk feels discomfort from 10am to 12pm. Users with west orientation desk feels discomfort from 2pm to 4pm. Users with south orientation desk feels discomfort from 8am to 4pm throughout the day. Users with north orientation desk don't receive required natural daylight as well as glare. Daylight distribution in the space is observed to be average by 82% users and not enough by rest users. Amount of view through windows is observed to be average by 73% users, inadequate by 9% users and adequate by 18% users. Quality of view through window is observed to be unpleasant by 18%, neither pleasant nor unpleasant by 46% and pleasant by 36%. The Sun in the office space is observed to be unpleasant by 55%, neither pleasant nor unpleasant by 18% and pleasant by 27%. The luminous environment of the office space is not satisfactory as per 73% users. Office uses artificial lighting for 5~7 hrs. by 55% users. Office users do not agree with the uniform distribution of natural daylight in the office space due to glare by 82% users and due to less availability of natural daylight by 18% users.

Useful insights obtained through the visual comfort questionnaire survey will be helpful to take necessary measures by the building owners and building designers and architects to improve the use of natural daylight in the office space and to increase the comfort level of the users which in turn can improve the office productivity, building energy-efficiency, and user wellbeing.

Figure 10

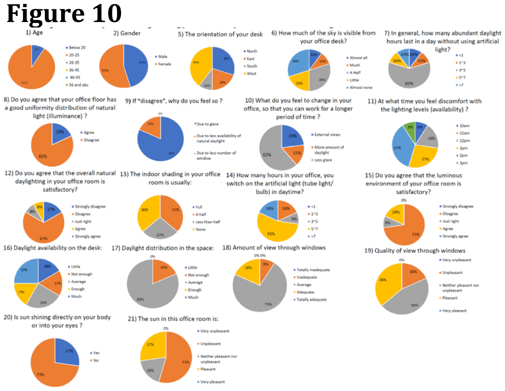

Figure 10 Responses of Visual Comfort Survey.
Source: Authors

KINETIC FAÇADE DESIGN PROCESS

CONCEPTUAL APPROACH

As per the researchers Tabadkani et al. (2018), Hosseini et al. (2019), Tabadkani et al. (2019), Hosseini et al. (2021), Tabadkani et al. (2021), the tri-fold kinetic façade minimizes negative spaces and creates a visually cohesive and dynamic architectural feature. Various features of tri-fold kinetic façade are shown in Figure 11. The angle of opening of the tri-fold kinetic façade of each module is incremented to every 5˚ for conducting daylighting simulations (see Figure 12).

Figure 11

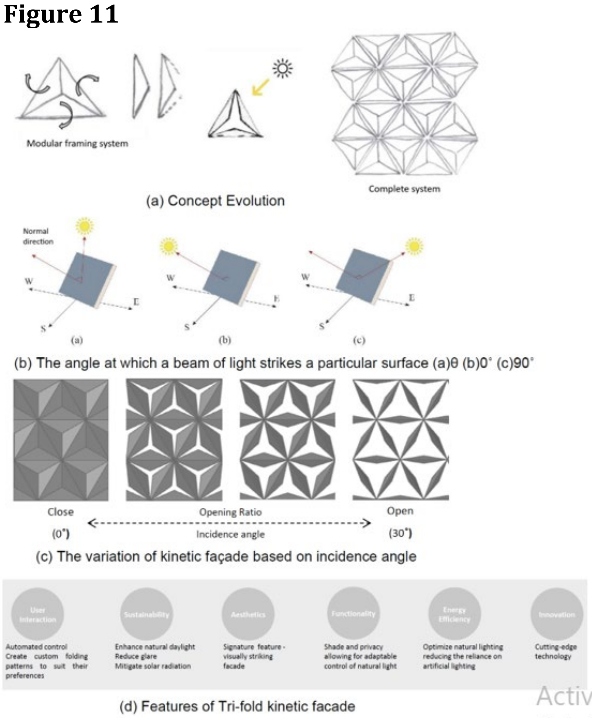

Figure 11 Features of Tri-Fold Kinetic Façade.
Source: Adapted by Authors

Figure 12

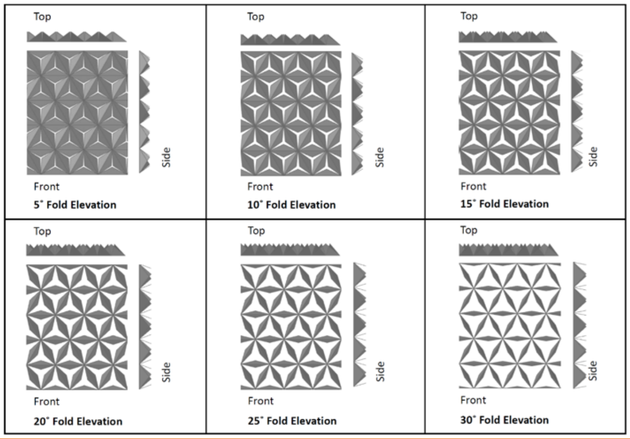

Figure 12 Kinetic Façade Angles with Top, Front and Side Elevation.
Source: Adapted by Authors

ARCHITECTURAL DETAILS OF KINETIC FAÇADE

The components of the proposed kinetic façade module are shown in Figure 11(a)and(b). The opening ratio of the kinetic façade panels varies from 0˚ to 30˚ (see Figure 11 (c)). Kinetic façade panels are mounted on a triangular grid frame work made of Aluminum section 25 x 25mm. Panel is connected to the frame with stainless steel cast hinge - 25 x 20mm gap (see Figure 13(c)). Sectional detail with the fixing position of the kinetic façade is shown in Figure 13(a). Each floor has a height of 3.6m between finished floor level (FFL) to FFL. The extended slab projection on every floor makes it viable to fix the external envelop easily. Being easily accessible through the curtain wall, cleaning and maintenance also becomes convenient. Grid framework for placing the kinetic façade modules is shown in Figure 13(b). Reyno bond- composite aluminum sheet is chosen as appropriate material for kinetic façade module that can contribute to a more sustainable and environmentally friendly building design.

Figure 13

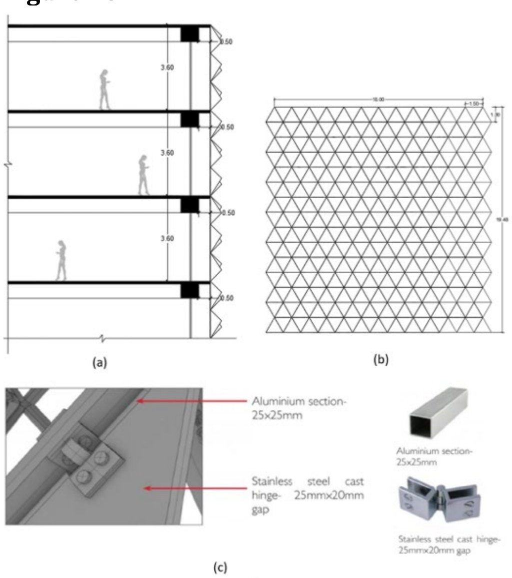

Figure 13 (a) Sectional Detail Showing the Fixing Position of the Kinetic Façade; (B) Grid Framework for Placing Kinetic Façade Modules; (C) Panel to Frame Hinge Joinery Details.
Source: Authors

DESIGN ITERATIONS

The list of parameters considered in the design iteration process through simulation tool is shown in Table 11.

Table 11

Table 11 List of Parameters Considered

Parameters	Input
Purpose	Visual comfort
Kinetic quality	Mutual shading Daylight amount and quality
Movement type	Fold
Application in project	South/ east/ west facade
Façade material	Reyno bond- composite aluminum sheet
Variable considered	Panel size: x=1m, x=1.5m and x=2m Folding angle: 5˚, 10˚, 15˚ and 20˚
Parameters for assessment	sDA, ASE and sDG (Disturbing Glare)
Control	Semi-Automated control
Pattern features	Completely mutable shading Reduce reliance on artificial lighting during the day by maximizing the utilization of natural daylight. Controlling solar gain, glare, and privacy

For x=1m

The first set of simulations is done for x=1m i.e., 4 kinetic panel modules vertically mounted for each floor. The angle of openings is incremented in multiples of 5 degree. The details are shown in Figure 14(a)(b)and(c). Simulation results for 10-degree fold are shown in Figure 15. Similar simulation analysis is done for other fold values as well. The findings from the analysis for different fold values are given in Table 12.

Figure 14

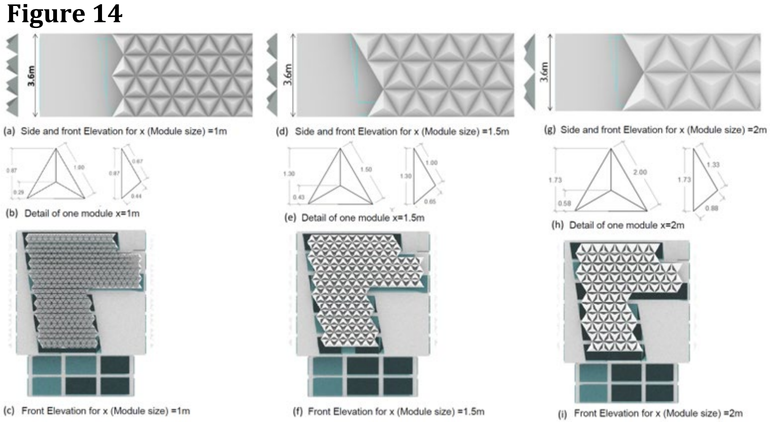

Figure 14 Details Regarding Different Selected Module Size.
Source: Authors

Figure 15

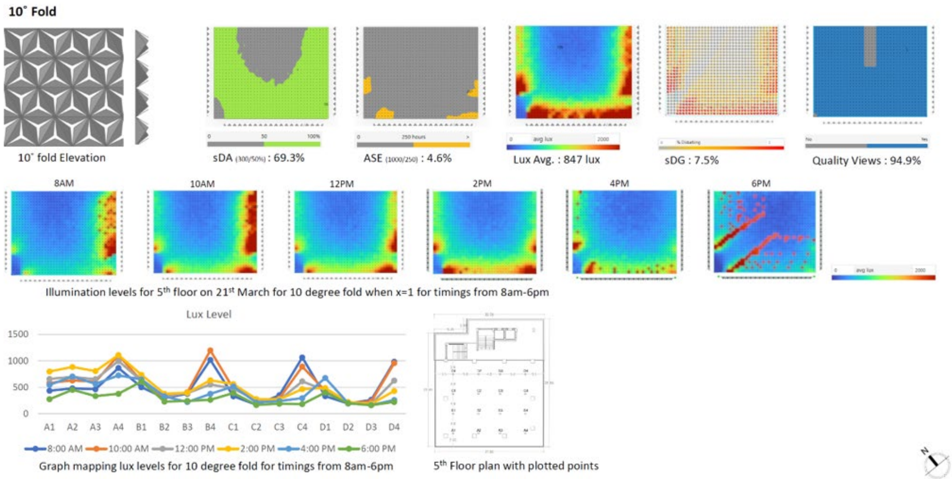

Figure 15 Simulation Results For X=1m and 10-Degree Fold.
Source: Authors and Rhino Software, Grasshopper (Ladybug and Honeybee Plugins)

Table 12

Table 12 Simulation results for x=1m.

Parameter	5°	10°	15°	20°
$sDA_{300/50\%}$	44.30%	69.30%	85.60%	96.90%
$ASE_{1000,250}$	3.10%	4.60%	8.20%	14.30%
Avg. annual lux value	552 lux	847 lux	1114 lux	1365 lux
Intolerable glare (sDG)	3.20%	7.50%	15.20%	21.60%
Quality views	94.90%	94.90%	94.90%	94.90%
LEED Compliant	1-credit	2-credits	3-credits	3-credits

For x=1.5m

Next set of simulations is done for x=1.5m i.e., 3 kinetic panel modules vertically mounted for each floor. The angle of openings is incremented in multiples of 5 degree. The details are shown in 14(d)(e)and(f). Simulation results for 10-degree fold are shown in Figure 16. Similar simulation analysis is done for other fold values as well. The findings from the analysis for different fold values are given in Table 13.

Figure 16

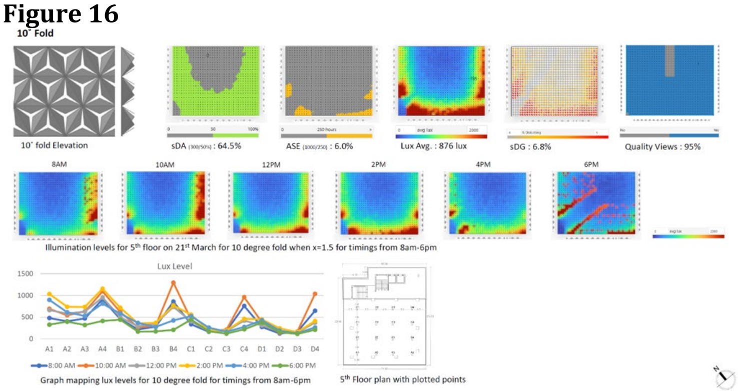

Figure 16 Simulation Results for x=1.5m and 10-Degree Fold.
Source: Authors and Rhino Software, Grasshopper (Ladybug and Honeybee plugins)

Table 13

Table 13 Simulation Results for x=1.5m.

Parameter	5˚	10˚	15˚	20˚
$sDA_{300/50\%}$	45.20%	64.50%	76.80%	88.60%
$ASE_{1000,250}$	4.30%	6%	9.80%	12.20%
Avg. annual lux value	621 lux	876 lux	1120 lux	1349 lux
Intolerable glare (sDG)	4.30%	6.80%	12.80%	18.60%
Quality views	95%	95%	95%	95%
LEED Compliant	1-credit	3-credits	3-credits	3-credits

For x=2m

Next set of simulations is done for x=2m i.e., 2 kinetic panel modules vertically mounted for each floor. The angle of openings is incremented in multiples of 5 degree. The details are shown in 14(g)(h)and(i). Simulation results for 10-degree fold are shown in Figure 17. Similar simulation analysis is done for other fold values as well. The findings from the analysis for different fold values are given in Table 14.

Figure 17

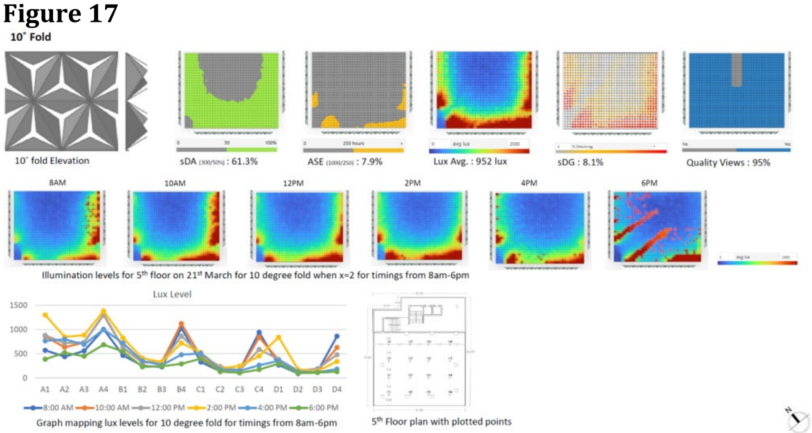

Figure 17 Simulation Results For x=2m and 10-Degree Fold.
Source: Authors and Rhino Software, Grasshopper (Ladybug and Honeybee Plugins)

Table 14

Table 14 Simulation Results for x=2m.

Parameter	5˚	10˚	15˚	20˚
$SDA_{300/50\%}$	46.50%	61.30%	72.60%	82.20%
$ASE_{1000,250}$	6.30%	7.90%	12.60%	15.10%
Avg. annual lux value	723 lux	952 lux	1174 lux	1380 lux
Intolerable glare (sDG)	6.20%	8.10%	12.80%	17.90%
Quality views	95%	95%	95%	95%
LEED Compliant	1-credit	3-credits	2-credits	3-credits

RESULTS OF THE DAYLIGHT SIMULATION

As per design iteration I, II and III, iteration II is considered as it shows better results compared with I and III with respect to sDA, ASE and sDG. After considering design iteration II, (i.e., x=1.5m) the daylight simulations are done for fifth floor of the office building, on the four important dates of the year, keeping time constant at 12:30pm - 21st March (equinox), 21st June (summer solstice), 21st September (equinox), and 21st December (winter solstice). The simulations are carried out for every 5˚ increment in the angle of opening of the kinetic wings. The results are obtained for – (i) Spatial Daylight Autonomy; (ii) Annual Sunlight Exposure, (iii) Point in-time daylight illuminance, (iv) Annual glare, and (v) View analysis. The simulations are not carried out beyond opening angle of 20˚ because it shows excessive glare. The results of the daylight simulations are shown in Figure 18.

Figure 18

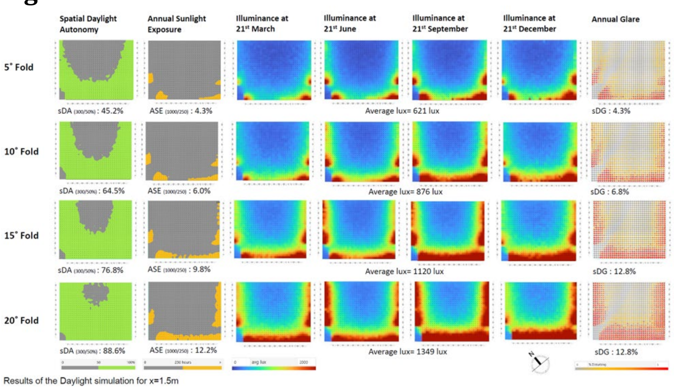

Figure 18 Results of the Daylight Simulation for x=1.5m.
Source: Authors and Rhino and Grasshopper (Ladybug and Honeybee Plugins)

In absence of the proposed kinetic façade, for the fifth floor of the office building the ASE value is calculated as 45.5% and annual disturbing glare (sDG) is calculated as 48.4% through simulation analysis. Hence, as per the details shown in Figure 18, by designing the proposed adaptive kinetic façade, ASE can be reduced by 73-90% and sDG can be reduced by 73-91% which is significant improvement. This will improve the indoor comfort condition by creating cooling effect. However, the detailed thermal performance analysis of the proposed kinetic façade is beyond the scope of the present research.

Design Iterations

A number of design iterations with all possible combinations of angle openings (specific angles with 5˚ increment, i.e., 5˚, 10˚, 15˚, and 20˚) on the three façade that are south façade, west façade and east façade are performed to evaluate the visual performance. For each month, 24 iterations with all possible angles are evaluated for each time period. In total, 144 iterations are evaluated for each month (see Figure 19). Here, 5˚ open means mostly closed and 20˚ open means more than 50% open. The best combinations of wing angles are selected based on its compliance with LEED daylighting standards. The daylighting metrics are sDA, ASE and Glare.

Figure 19

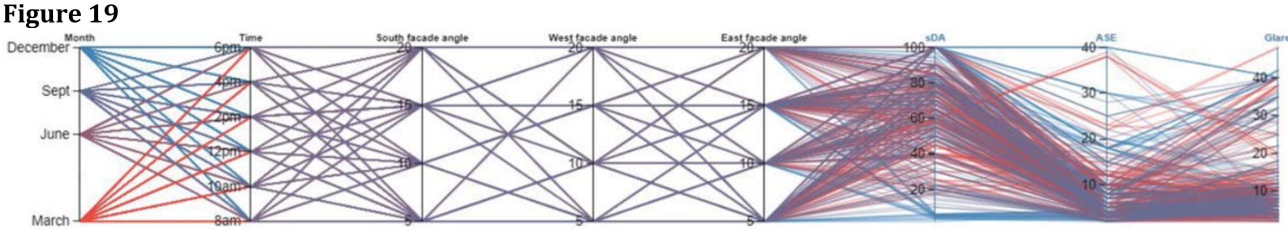

Figure 19 Combination of Opening Angles and its Daylighting Performance.
Source: Authors and Design Builder

Optimal Opening Angle of Façade Panel

As per the simulation analysis, optimal opening angles and daylighting plans in terms of sDA, ASE and glare for respective opening angles of south, east and west facade for 21st March, 21st June, 21st September, and 21st December at timings from 8am-6pm are shown Figure 20, 21, 22 and 23 respectively.

Figure 20

21st March

Time	South façade angle	West façade angle	East façade angle
8am	10°	15°	5°
10am	15°	20°	10°
12pm	15°	10°	15°
2pm	10°	5°	10°
4pm	10°	15°	20°
6pm	15°	10°	15°

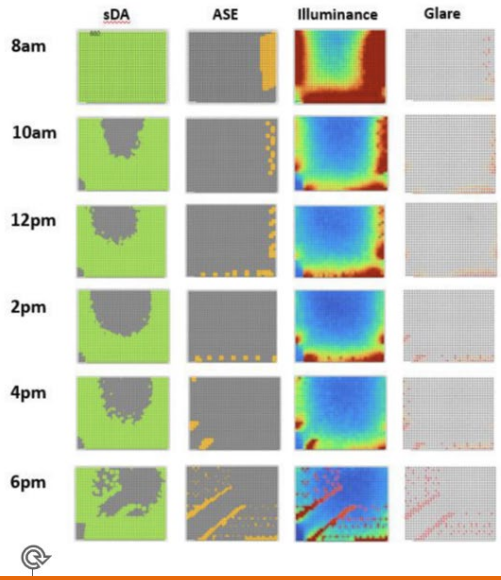

Figure 20 Optimal Opening Angles and Daylighting Plans for 21st March.
Source: Authors

Figure 21

21st June

Time	South façade angle	West façade angle	East façade angle
8am	20°	20°	15°
10am	15°	20°	10°
12pm	10°	15°	20°
2pm	10°	15°	20°
4pm	15°	10°	15°
6pm	10°	15°	5°

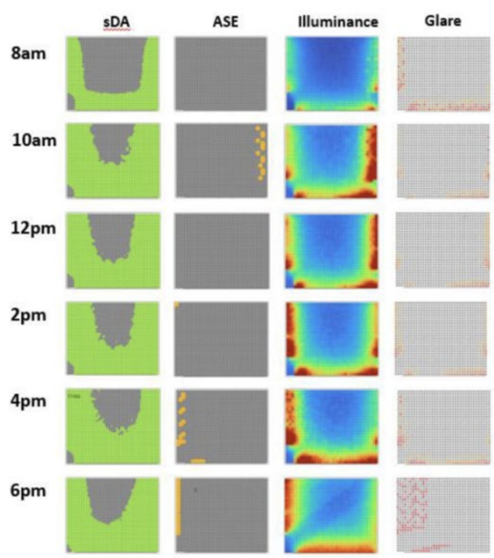

Figure 21 Optimal Opening Angles and Daylighting Plans for 21st June.
Source: Authors

Figure 22

21st September

Time	South façade angle	West façade angle	East façade angle
8am	15°	20°	10°
10am	20°	10°	15°
12pm	20°	10°	5°
2pm	10°	5°	15°
4pm	15°	15°	5°
6pm	10°	15°	5°

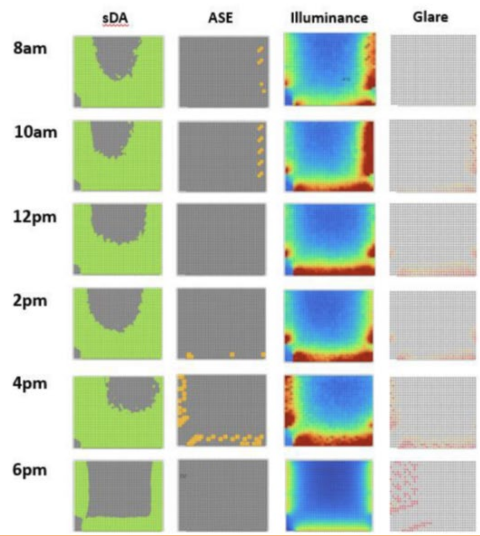

Figure 22 Optimal Opening Angles and Daylighting Plans for 21st September.
Source: Authors

Views of Proposed Kinetic Façade

A tri-fold kinetic façade has been designed to enhance the visual performance of a building, as well as to create a dynamic and interactive architectural feature that also improves the functionality and aesthetic quality of buildings. The detailed 3D view and elevations of the office building with the proposed kinetic façade is shown in Figure 24.

Figure 24

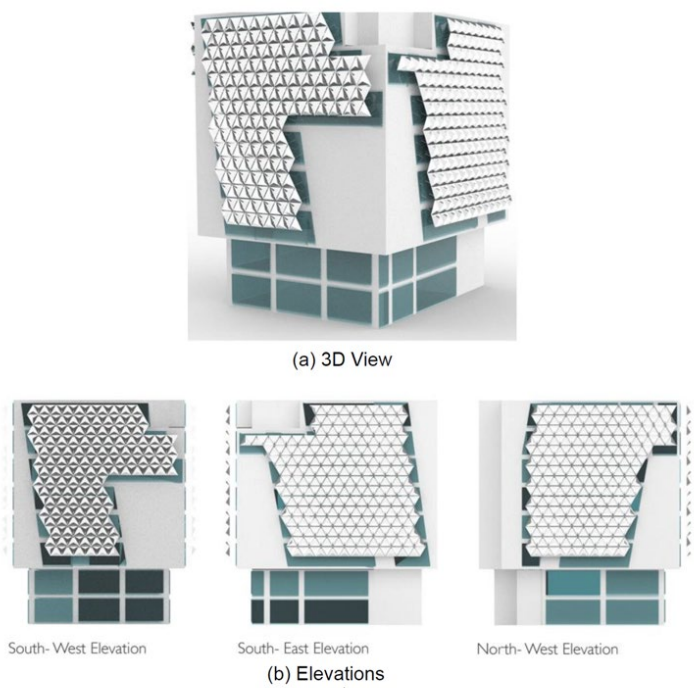

Figure 23 View and Elevations of the Office Building with the Proposed Kinetic Façade.
Source: Authors

CONCLUSION

One of the crucial aspects of the scientific process is replicability. This study presents a novel computational approach by integrating simulation tools with design process in real time that enables a wide range of stakeholders, including architects, designers, researchers, and students, to investigate and analyze the impact of kinetic facades on visual comfort metrics. By employing an optimization framework, the study addresses the critical stages of achieving optimal interior illuminance and user visual comfort in the office building, demonstrating the novelty and effectiveness of the proposed approach. Further, the results obtained from the calculation by the simulation tool are validated with the data obtained through on-site physical measurement which indicates the robustness of the proposed computational approach. Although, aspects of thermal performance, energy-efficiency, etc. can be added to this framework in the future research-works to further assist in the optimal design of building façade.

Looking forward, the development of adaptive kinetic pattern design will be a significant priority in computational design theory and practice, particularly in the context of parametric design systems. While devising a new pattern parametric design strategy can be a challenging task, utilizing existing design strategies as a reference point could serve as a useful guideline for generating kinetic patterns.

The findings of the study provide valuable insights into the potential of kinetic facades to enhance visual comfort, highlighting the importance of continued research and development in this field. The study's approach and tool can help architects and designers in developing effective and sustainable facade design solutions that prioritize user comfort while simultaneously meeting performance and aesthetic requirements. Overall, this study represents a crucial step towards achieving optimal visual comfort in buildings, and it opens new avenues for future research in this area.

ACKNOWLEDGMENTS

None.

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