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Assessing the Effect of Building Skin Adaptability on Energy Consumption in Hot Arid Regions

Sara Khelil [1], Alla Eddine Khelil [2], Tallal Abdel Karim Bouzir [3], Djihed Berkouk [1], Noureddine Zemmouri [1]

[1] Department of Architecture, University of Biskra, Biskra, Algeria
[2] Escuela Técnica Superior de Arquitectura, University of Seville, Seville, Spain
[3] Institute of Architecture and Urban Planning, Blida University, Blida, Algeria

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Abstract

Building skins have a vital role in energy efficiency, particularly in terms of the conservation or consumption of energy. Many factors must be considered by designers to prevent wasting significant quantities of energy, to preserve and provide internal air conditioning and lighting, particularly in hot dry locations where the integration of sun protection systems is highly recommended. This pilot study looks at the challenge of developing energy-efficient building skins in hot regions like Biskra city by applying a natural daylight strategy represented by a parameterised moveable shading component to the skin of a hospital patient's room. In this research, we aim to assess the adoption of building skin parameterisation as a beneficial technique for reducing energy consumption and improving internal temperature and lighting in this environment by developing and implementing a computational design methodology. Promising experimental results demonstrate the benefit of this proposal. The use of parameterisation in the design of patient's room skins, with moveable, tightly folded morphology, providing self-shading, are essential and effective techniques for ensuring good natural lighting and reducing both temperature and energy consumption..

KEYWORDS

Building's skin, energy efficiency, harvesting daylighting, hot and arid regions, kinetic architecture, parametric design

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1. Introduction

In the context of climate change, energy efficiency, and renewable energy, we are looking for novel energy optimisation techniques leading to the identification of designs and technologies that will reduce energy use and maximise energy saving in hot and dry locations (Sansaniwal *et al.*, 2021).

To address this challenge, we are concentrating on the installation of energy-efficient technology, particularly in building skins (Huang *et al.*, 2020). Because they operate as intermediary filters between conditions in the external environment and the functional requirements of the internal occupants (Karaseva and Cherchaga, 2021), building skins play an essential role in the management and control of lighting, thermal comfort, and energy consumption (Bowman *et al.*, 2021; Kalousek, 2021; Jalloul, 2020).

Because of these critical functions, building skins have been the focus of several research studies in recent years (Knippers *et al.*, 2012; Kolarevic, 2015), with the aim of improving efficiency and performance in terms of energy, comfort, or structure (Attia *et al.*, 2020; Odiyur Vathanam *et al.*, 2021; Elchishcheva *et al.*, 2021; Alkhatib *et al.*, 2020).

One of the most important comfort aspects of a building's is the lighting, which has a direct and substantial impact on people's health (Frontczak and Wargocki, 2011). Lighting influences mood and human circadian cycles (Heschong, 2002), which go beyond the safety considerations of giving adequate illumination to see. Glare, headaches, skin problems, eyestrain, and different forms of sight loss can all be caused by poor illumination. Designers, building owners, and tenants must address these concerns (Mesloub *et al.*, 2019a; Bluyssen, 2019).

Studies on natural lighting have traditionally concentrated on schools, offices, and commercial buildings, despite healthcare buildings being the most impacted, particularly considering people who are bedridden (Ju-Yoon and Kyoo-Dong, 2017; Eijkelenboom *et al.*, 2020). Due to large internal loads, healthcare facilities are usually regarded as significant energy users (Sun *et al.*, 2020). This is worsened in dry locations by the high demand for cooling caused by intense sun exposure.

Designing for health has a long history, but it was addressed in many approaches and was labelled as alternative or supplementary medicine, affecting both staff and patient well-being (Baker and Koen, 2014; Eijkelenboom *et al.*, 2019). Design guidelines require the provision of external windows in these buildings (Boyce *et al.*, 2003; Choi *et al.*, 2012), providing daylight and access to the outside world (Sadatsafavi *et al.*, 2015), while also increasing sun penetration in hostile desert climates (Phiri and Chen, 2013; Quan *et al.*, 2011).

Careful design of windows and associated shading systems can aid in lowering total energy loads while maintaining aesthetic comfort (Roessler, 1980; El Sheikh, 2011). Virtual imitations of nature, natural lighting, artwork, soothing hues, and therapeutic music have been shown by scientific experts to substantially speed the healing process and provide a less stressful healthcare environment (Ulrich, 2001; Heerwagen and White, 1998; Barlow *et al.*, 2009; De Giuli, 2013; Mariëlle *et al.*, 2018).

Kinetic systems that react to different levels of solar radiation are by far the most common adaptive façade solution (Attia *et al.*, 2020). There are examples of micro, macro and combined systems, but computer-controlled macro systems are the most common. There are many different shapes and forms of adaptive solar shading systems. There are external shading devices like those proposed by Alkhatib *et al.* (2020), Karaseva and Cherchaga (2021) and Kalousek (2021) and internal systems as proposed by Bowman *et al.* (2021); different kinds of blinds and shutters but also more innovative examples both concerning shape and appearance and also in terms of the driving mechanism.

A common method to reduce solar heat gain is to use windows that have an additional coating as described by Kalousek (2021). These

Corresponding Author: Sara Khelil 00213558226702, sara.khelil@univ-biskra.dz

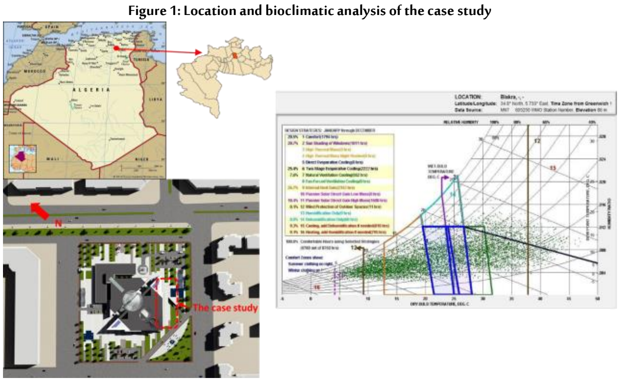
coatings can be of different kinds but have one thing in common, under influence of high levels of radiation, high temperature or an electric current they can change their transparency and thus reflect heat radiation, preventing it from entering the room. This is an example of a commonly used micro level system, but now it has the drawbackthat it cannot be overridden.

Karaseva and Cherchaga (2021) presented another adaptive solution which is to allow the U-value of the walls to alter according to the heat load from the surroundings. This could be achieved in several different ways, for example by introducing controlled airflow in the wall cavity or using moveable insulation panels that can be repositioned to a configuration that is suitable for current external conditions.

There are several different concepts that use the response to water as a mechanism for change as stated by Cao *et al.* (2021). Material like the well-known fabric Gore-Tex does not change *per se* but behaves differently depending on the state of the water. It allows water vapour to penetrate but blocks the liquid form. Conversely, other materials called hygrodiodes exist that grant liquid water unlimited access while preventing the entry of water vapour. While Gore-Tex is a polytetrafluoroethylene(PTFE)-based polymer, a hygrodiode is a layered construction that allows water to penetrate by capillary suction through a felt-like material. There are also materials that alter their properties depending on the relative humidity of the surroundings.

The city of Biskra, Algeria (Figure 1), is in a hot, dry region. It has a harsh climate with very hot, dry summers and very cold winters (Khelil *et al.*, 2016). These characteristics challenge the achievement of thermal and visual comfort. The construction of building skins in this location must tale many factors into account to prevent huge wastage of energy to maintain interior comfort.

Figure 1: Location and bioclimatic analysis of the case study



According to the bioclimatic analysis of Biskra (Figure 1), the city is outside the thermal comfort zone for most of the year (only 20.5 percent of the year is naturally comfortable). Shielding from direct solar radiation is one of the most common strategies to achieve thermal comfort (Ioannou and Itard, 2017) and minimise energy consumption in buildings in this location during the summer season (Shariful *et al.*, 2010; Mesloub *et al.*, 2019).

We conducted a research project in this region to develop sustainable and energy efficient architecture. The most crucial design challenges in hot, arid regions involve thermoregulation and light harvesting (Cao *et al.*, 2021; Naglaa, 2016; Laracuente, 2015). We applied a kinetic shading system to the building skin and proposed a novel system to optimise heat gain, daylight harvesting and energy efficiency. This study is an examination of the efficiency of the proposed dynamic building skin, in a south-east facing patient's room.

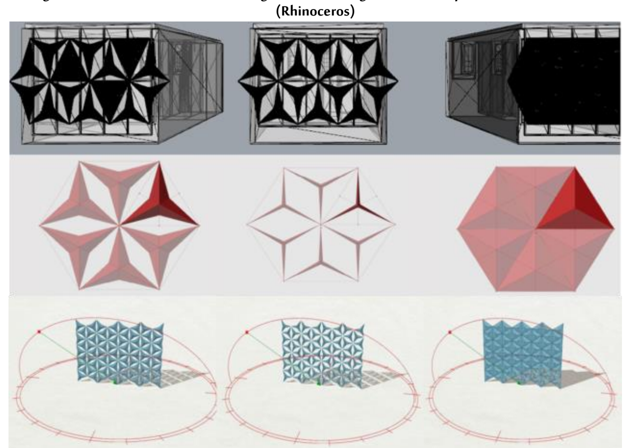
The room in the case study has rectangular geometry with dimensions of 8.30 m x 5.50 m and a height of 4.00 m. The window facing south-east is 3.00 m in length and 1.40 m in height and from the windowsill to the floor is 0.85 m. The surface reflectances are 20% for the floor, 90% for the ceiling, 50% for the walls and 80% for the window glass. This study seeks to assess the proposal's daylight harvesting, thermal and energy performance, and the introduction of detection systems and adaptiveness to building skins.

This system can change its configuration in response to the surroundings using established design criteria. When it is dark, the entire system can be shut down, but when daylight is good, the system is fully operational.

The shading panels open and close as follows (Figure 2):

- Maximum opening of the shade panel when it is in the shade: 100% radiation penetrating inside the building
- Partial opening of the shade panel when it is partially exposed to the sun 25–50% of radiation penetrating inside the building
- Total closure of the shade panel when fully exposed to the sun: 0% radiation entering the building

Figure 2: The reference model showing different configurations in response to solar radiation (Rhinoceros)



2. Materials and Methods

In this section, we present the experimentation protocol (parametric performance evaluation of the proposal) to assess the environmental performance of the kinetic shading device, using the following parametric modelling tools: Grasshopper for Rhino, Ladybug plugin, Honeybee plugin, Energy plus, Diva and Ecotect.

Because of the complex proposal's geometry and the relatively easy management of geometric variables, the proposed shading device was modelled in a parametric environment. Some of the most interesting elements of parametric tools include data manipulation, interaction with other tools, and simulation possibilities, and this led us to create the geometry of the base-case patient's room and the integrated kinetic shading device in Rhinoceros. All the elements of the model were parametrically controlled in Grasshopper, using the plugin Honeybee, to connect it to specialist simulation software.

For the assessment of the shading system with the optimum performance, a combination of thermal, lighting (visual) comfort, and energy indices was used under dynamic conditions. Four evaluations were produced:

- Thermal behaviour of the patient's room
- Patient's room illumination analysis, daylight factor, daylight autonomy and radiation
- Estimation and optimisation of the solar gain
- Energy consumption of the patient's room

The evaluation was carried out by comparing the cooling/heating loads as well as the energy consumption of the case study patient's room with and without the integrated building skin. All the materials were determined from Honeybee's Radiance material component database and allocated to each surface. To facilitate the evaluation of the proposal three contraction patterns have been considered 25%, 50% and 75%.

Two experimental design days, design day 1 (DD1) and design day 2 (DD2), were selected for the simulation. Their selection was based on daily averages of solar radiation (Table 1) and temperature variables (Table 2). DD1 was the day with the highest (maximum) temperature (t) and highest (maximum) solar radiation (during the hot period), and DD2 was the day with the lowest temperature (t) and lowest solar radiation (during the cold period). The challenge for this research is to cover the range of temperatures and solar radiation levels over a 365-day period. The days DD1 and DD2 were chosen to measure these two criteria at their maximum and minimum values, respectively.

In the problem of design day selection, multi-objective optimisation techniques are used to concurrently optimise (maximise or minimise) these criteria. DD1 is 22nd July, which represents the brightest and hottest day. DD2 is 1st January, which represents the most overcast and coldest day.

Table 1: Average daily and monthly solar radiation, in Biskra city

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average daily radiation	6.3	8.2	9	9.7	10.3	11.2	12.4	11.5	10.5	8.2	7	7
Average monthly radiation	216	230	278	290	320	337	383	355	314	254	210	219

Table 2: High and Low Temperature in Biskra city

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
High	15°C	19°C	22°C	26°C	31°C	37°C	40°C	39°C	34°C	28°C	21°C	17°C
Low	6°C	9°C	12°C	15°C	20°C	25°C	28°C	28°C	24°C	18°C	12°C	8°C

3. Results and Discussion

In this section, we present the simulation results. Outcomes are represented graphically in each case for clarity, ease of understanding and comparison purposes. The results are categorised into four sections as listed in the Materials and Methods (Section 2)

3.1. Thermal Behaviour of the Theoretical Base Case Patient's Room

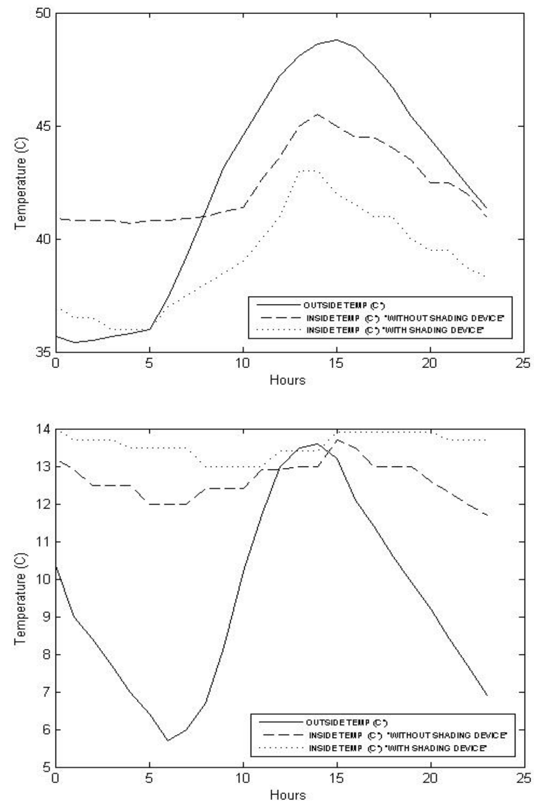
As explained in the previous section, we evaluated the thermal behaviour of the theoretical case study patient's room. The indoor air temperature and the optimisation of temperature control during the overheating period were analysed before and after implementation of the proposed system.

The graphs (Figure 3) compare three temperature profiles for the experimental design days (DD1 and DD2) to assess the thermal efficiency and performance of the proposed system:

- The current case: interior temperatures without integration of the proposed system
- The interior temperatures after the implementation of the proposed system
- External temperatures

By interpretation of the graphs, we notice an improvement of the temperatures for the two design days in the case of the patient's room with the proposed system, where the difference registered between the two cases for DD1 is of 4° and for DD2 is of 2°.

Figure 3: Comparison of indoor air temperatures of the base-case (with and without the proposed system) Top: During DD1. Bottom: During DD2.



Due to the implementation of the suggested system in the case study, an optimisation of temperature control during the overheating period is seen, leading to a significant temperature drop of between 3°C and 3.7°C, which is important for the building's energy performance. It should also be noted that, despite the use of this technology to reduce the temperature during the overheating period that defines the hot, arid local environment, overheating has not been completely eliminated. This minor problem is because the device is not integrated with any other cooling solutions.

3.2. Patient's Room Illuminance Analysis, Daylight Factor, Daylight Autonomy and Radiation

DIVA for Rhino software was used to evaluate natural lighting in the case study. A series of simulations was carried out to study the influence of kinetic facades on the lighting of healthcare facilities. The aim was to show the effect of intelligent kinetic shading on buildings with glass facades. The shading device must be able to adapt to the specific environmental conditions at its location. The weather files for Biskra on the two specified design days were used for this analysis.

Based on the results obtained on DD1, we observe that with the presence of the proposed kinetic shading device, 62% of the area was between 200 and 500 lux. In the subject area, 8% of the area had more than 500 lux while 30% had less than 200 lux with clear skies. On the same day and without the kinetic shading system, 68% of the area was between 200 and 500 lux, 13% of the area received illuminance levels above 500 lux and 19% received illuminance levels less than 200 lux (Table 3).

However, for DD2, with the proposed kinetic shading device, 67% of the area was between 200 and 500 lux. In the subject area, 22% of the area had more than 500 lux while 11% had less than 200 lux with clear skies. On the same day and without the kinetic shading system, 65% of the area was between 200 and 500 lux, 7% of the area received illuminance levels above 500 lux and 28% received illuminance levels less than 200 lux (Table 3).

Table 3: Illuminance levels for DD1 and DD2 with clear skies

Illuminance level (lux)	DD1		DD2	
	Percentage of the Subject area without shading device %	Percentage of the Subject area with shading device %	Percentage of the Subject area without shading device %	Percentage of the Subject area with shading device %
200- 500	68	62	65	67
Above 500	13	8	7	22
Below 200	19	30	28	11

A remarkable enhancement in the illuminance values is revealed, in the case of the patient's room with the responsive shading device, where we had the ability to reach the recommended illuminance values for normal purposes in the patient's room in the region of Biskra.

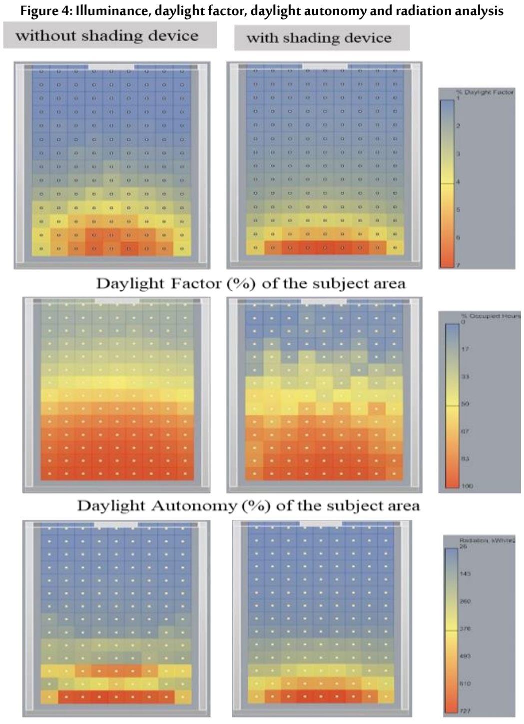
Concerning the daylight factor, 68% of all illuminance sensors have a daylight factor of 5.2% during the occupancy period for the case of the subject area without shading device (Figure 4). However, in the case of the subject area with the shading device, 38% of the illuminance sensors have a daylight factor of 3%.

For daylight autonomy (DA), in the case of the model without the shading device (Figure 4), about 50.8% of the studied area had an spatial DA of 300 lux for more than 60% of the occupied hours. For the second case of the study (with the shading device), 46% of the space has a spatial DA of 360 lux for more than 60% of the occupied hours.

When analysing the radiation maps of the subject area, with and without the shading device, we distinguish an enhancement of the solar penetration in the second case, which is favourable in such climatic contexts for thermal comfort.

Based on the simulation results obtained, it appears that the suggested shading device should be regarded as a passive method for ensuring adequate natural lighting in the patient's room, where the kinetic shading device's functionality is directly dependent on the sun's path. Comparison of the patient's room with and without a kinetic shading system, reveals a performance gap that allows an ideal solution to be considered that meets the requirement for improved lighting.

Figure 4: Illuminance, daylight factor, daylight autonomy and radiation analysis



3.3. Estimation and Optimisation of the Solar gain:

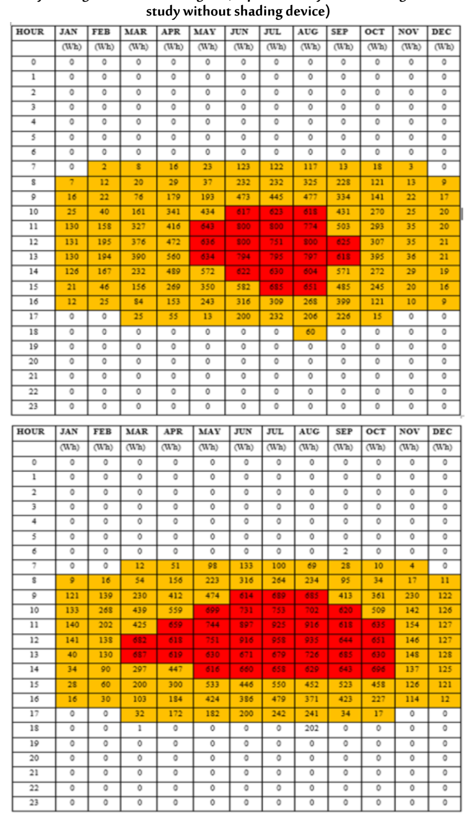
Very strong solar radiation characterises the city of Biskra with an insolation exceeding 3500 Wh / year and a direct solar radiation of 900 to 1100 W / m² vertically. In this section, we present simulation results concerning the monthly averages of the annual loads for the case study before and after the integration of the proposed system. Secondly, we present how the orientation of the building could affect the solar gain in the case study (with and without the bio-kinetic system).

3.3.1. Monthly Averages of the Annual Loads (Direct Solar gain)

Figure 5 presents an estimation of monthly averages for the solar gain throughout the year for the case study with and without the kinetic shading device. In the research, we have defined the amount of incident solar radiation for the city of Biskra at 613W / m² (ASHRAE, 2009). This value represents the direct radiation threshold and therefore all values above this value have the periods of undesirable solar gain. Using this threshold and according to the presented results, we notice that an optimisation of monthly averages of direct solar gain in the case study with the proposed system, where the period of undesirable solar gain is decreased.

In the base-case without the kinetic system, the period of undesirable solar gain is eight months, from March to October. However, for the base-case with the proposed system this period is decreased to five months, from May to September.

Figure 5: Monthly averages of Direct Solar gain (Top: case study with shading device / Bottom: case study without shading device)



HOUR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)
0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0
7	0	2	8	16	23	123	122	117	13	18	3	0
8	7	12	20	29	37	232	232	325	228	121	13	9
9	16	22	76	179	193	473	445	477	334	141	22	17
10	25	40	161	341	434	617	623	618	431	270	25	20
11	130	158	327	416	643	800	800	774	503	293	35	20
12	131	195	376	472	636	800	751	800	625	307	35	21
13	130	194	390	560	634	794	795	797	618	395	36	21
14	126	167	232	489	572	622	630	604	571	272	29	19
15	21	46	156	269	350	582	685	651	485	245	20	16
16	12	25	84	153	243	316	309	268	399	121	10	9
17	0	0	25	55	13	200	232	206	226	15	0	0
18	0	0	0	0	0	0	0	60	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0

HOUR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)
0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	2	0	0	0
7	0	0	12	51	98	133	100	69	28	10	4	0
8	9	16	54	156	223	316	264	234	95	34	17	11
9	121	139	230	412	474	614	689	685	413	361	230	122
10	133	268	439	559	699	731	753	702	620	509	142	126
11	140	202	425	659	744	897	925	916	618	635	154	127
12	141	138	682	618	751	916	958	935	644	651	146	127
13	40	130	687	619	630	671	679	726	685	630	148	128
14	34	90	297	447	616	660	658	629	643	696	137	125
15	28	60	200	300	533	446	550	452	523	458	126	121
16	16	30	103	184	424	386	479	371	423	227	114	12
17	0	0	32	172	182	200	242	241	34	17	0	0
18	0	0	1	0	0	0	0	202	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0

3.3.2. Impact of Orientation on the Optimisation of Solar Gain

The amount of solar gain is strongly related to the building's orientation. In this section, we present the results of the solar gain simulation for the base-case in three orientations (east-, south-, and west-facing) and for four scenarios:

- **1**: Case study without shading panel (glazing only)
- **2**: Case study with shading panel 25% opened
- **3**: Case study with shading panel 50% opened
- **4**: Case study with shading panel 75% opened

Table 4 presents the comparison of the simulation results for the base case annual gains for the east-, south- and west-facing orientations under the different shading panel scenarios. From the results obtained, we see that the south-facing orientation has the most intense solar gain (22.4%) relative to the west-facing orientation (14.5%) and the east-facing orientation (9.7%), for the base-case without the kinetic shading device. Solar gain is intense in the summer period for all the presented cases.

For the second scenario, with the shading panel 25% opened, we see a reduction in the amount of solar gain especially for the south-facing orientation (4%) but also for the east- (1%) and west-facing orientations (2%). The third scenario, with the shading panel 50% opened, presents a reduction of 7.3% for the south-facing orientation. However, a reduction of 1.4% is obtained for the east- and 2.4% for the west-facing orientations. Concerning the last scenario, with the shading panel 75% opened, we see a significant reduction of solar gain: 8.5% for the south-, 2.1% for the east- and (4%) for the west-facing orientations.

Based on these results, we find that the south-facing orientation is the most critical orientation in terms of solar gain, especially in the summer. The fourth scenario, with shading panel 75% opened, seems to be the most optimal case.

Table 4: Comparison of annual estimated solar gain for the case study with and without the shading panel

Orientation	Without shading panel %	With shading panel %		
		Opened 25%	Opened 50%	Opened 75%
East	9.7	8.3	8.3	7.8
South	22.4	19	15.7	14.9
West	14.5	12.6	12.2	10.7

3.4. Energy Consumption of the Patient's Room

The energy analysis was based on a 1-hour energy simulation for each of the four modelled building skin scenarios with the three orientations (south-, east-, and west-facing). The calculated daily load was for the case study patient's room and was based on the previously selected simulated design days. The patient's room was considered thermally controlled between 08:00 and 17:00 hours.

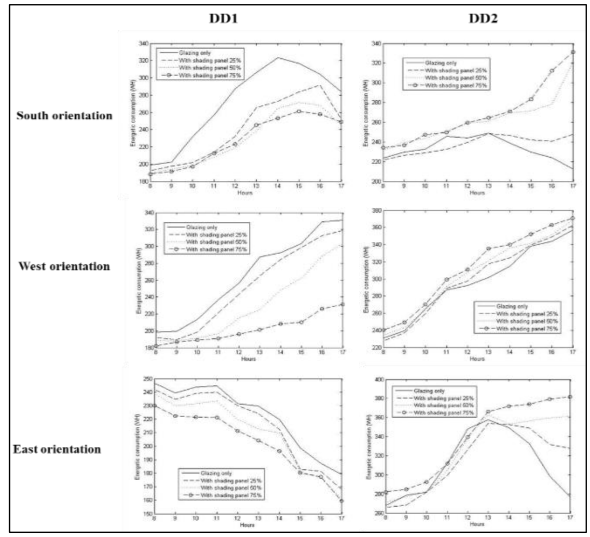
Figure 6 presents the energy consumption simulation results of all the scenarios. In summary, Tables 5 and 6 were developed to collate the results for all configurations in terms of their energy consumption during the period of their activation.

For the south-facing orientation, it is observed that for DD1 there is a decrease in energy consumption with a slight difference between the different scenarios. The fourth scenario seems be the most optimal for this case. However, for DD2, it is shown that there is an increase in energy consumption. This difference is slightly higher for the third and fourth scenario; however, the second scenario seems to be the most optimal.

In the energy consumption simulation results for the west-facing orientation, we notice that the energy consumption for DD1 decreases while using the proposed secondary skin. If the opening of the system increases, the energy consumption decreases. However, the difference in energy consumption between using the proposed kinetic system and glazing only is marginal for DD2.

It is observed in the energy consumption simulation results for the east-facing orientation for DD1 that the energy consumption for the first hours of the day is high and it starts to decrease at 11:00 for all the scenarios. The results obtained show an improvement in energy consumption in the second, third and fourth scenarios. However, for DD2, we notice a slight difference in the energy consumption between the four scenarios until 13:00, where no significant improvements are noticed. After 13:00, we see the energy consumption for the first scenario decreases However in the three remaining scenarios it increases. The fourth scenario presents the highest energy consumption.

Figure 6: Base-case energy consumption (DD1, DD2)



The results in the tables (Tables 5 and 6) show efficient outcomes during DD1 and DD2. When compared to buildings with the shading device (25%, 50% or 75% open), the static configuration (glazing only) has inefficient energy performance. In addition, the glazing-only scenario does not accommodate the daily solar cycle, and so does not improve the internal environment. It is useful at certain times and altitudes, but not throughout the entire day.

Therefore, the suggested kinetic shading device is primarily designed to respond to climatic and environmental variables, whereas glazing only is unable to react to these variables.

Table 5: Comparison of the energy consumption of the different secondary skin configurations (DD1)

Secondary skin configuration		Watt Hours consumption of all skin configurations									
		Dynamic simulation DD1									
		8H	9H	10H	11H	12H	13H	14H	15H	16H	17H
East orientation	Glazing only	246.7	239.2	243.8	244.7	231.3	229.6	219.8	198.6	187.3	179
	With shading device 25% open	242.1	234.6	239	239.9	230	224	212.3	183	181.3	167.9
	With shading device 50% open	238.7	229.9	231.3	233.4	219.7	212.8	209.8	181.2	176.8	161.2
	With shading device 75% open	230	222.3	221.5	221.2	211.3	204.3	196.3	180.2	177.2	159.6
South orientation	Glazing only	198.7	202.3	231.7	256.8	287.2	306.1	323.2	316.8	304.1	283.9
	With shading device 25% open	192.3	197.4	201.7	213.9	232.1	265.3	272.9	283.5	291.6	252.3
	With shading device 50% open	189.5	194.3	198.6	208.5	218.9	238.4	264.3	271.3	268.3	245.3
	With shading device 75% open	188.4	191.3	197.3	212.3	223.4	245.3	253.2	261.3	257.8	248.9
West orientation	Glazing only	198.4	199.2	213.4	236.9	256.7	287.5	292.4	303.2	328.9	331
	With shading device 25% open	192.1	189.4	198.4	221.3	243.5	264.8	284.5	298.4	312.4	318.9
	With shading device 50% open	188.6	188.2	191.3	196.4	215.3	225.3	248.5	262.1	288.5	303.1
	With shading device 75% open	182.1	186.8	189.2	191.2	196.3	201.3	208.5	210.4	226.3	231.4

Table 6: Comparison of the energy consumption of the different secondary skin configurations (DD2)

Secondary skin configuration (scenarios)		Watt Hours consumption of all skin configurations									
		Dynamic simulation DD2									
		8H	9H	10H	11H	12H	13H	14H	15H	16H	17H
East orientation	Glazing only	267.9	278.8	282.1	312.1	348.2	357.6	349.3	332.6	298.6	276.8
	With shading device 25% open	265.9	268.4	281.9	299.6	326.7	353.9	352.6	348.9	332	327.9
	With shading device 50% open	271.3	276.9	282.4	304.9	338.6	362.8	353.1	356.2	359.5	361.3
	With shading device 75% open	282.1	284.8	292.7	311.6	339.5	366.3	372.1	374	379.3	381.9
South orientation	Glazing only	223.4	229.6	232.7	245.7	243.9	249.1	238.6	229.7	224	212.6
	With shading device 25% open	221.4	226.3	228.9	232.7	239.4	248.6	246.3	242.1	240.7	247.8
	With shading device 50% open	231.4	239.6	243.5	251.3	258.9	261.3	269.3	271.3	278.5	321.3
	With shading device 75% open	234.3	236.7	247.4	249.7	259.4	264.3	271.1	283.5	312.4	331.3
West orientation	Glazing only	231	239.4	265	287	292.1	301.8	314.6	337.9	343.8	356.9
	With shading device 25%	227.8	237.3	259.5	288.9	297.4	317.4	324.5	339.5	348.9	362.5
	With shading device 50%	234.2	243.1	263.6	291.4	307.9	321.4	336.1	341.3	351.4	369.1
	With shading device 75%	240.2	249.4	270.1	299.1	311.2	335.4	340.1	352.2	363.1	371

In this study, we explained how the integration of kinetic skins with the thermal regulation and lighting systems of buildings can increase energy efficiency and enhance indoor comfort. The main contribution of this research is a dual methodology for the design and evaluation of kinetic skins, using parametric design as an alternative platform for designers to improve, validate and make informed decisions during early design development while offering unprecedented ways to explore design options and strategies to optimise kinetic facades for environmental performance.

The parametric tools were useful in determining the best combination of the different design elements to achieve a balance of the performance objectives. The findings also aided in understanding the combined influence of the design elements on performance. However, computational software alone was insufficient since we needed to manually adjust the selected outcomes to improve their performance further. This underlines the importance of the architect, even in a design method that is mainly computational.

4. Conclusion

Throughout this research, we aimed to test the reliability and environmental performance of the proposed kinetic shading device to assess the effect of the adaptability and parameterisation of a building's skin on energy consumption, while optimising internal temperatures and access to daylight.

When the results of the energy consumption, thermal and daylighting simulations are combined, the proposed parameterised kinetic shading system clearly has a significant influence on thermal comfort, access to daylight, and energy consumption. When the outcomes of DD1 and DD2 are compared, it is clear that DD1 (representing the hot period) achieves more savings than DD2 (representing the cold period). One cause for this disparity might be that direct entry of solar radiation plays a key role in heat transfer in buildings during the winter, but heat transfer into buildings during the summer is mostly owing to the temperature differential between the interior and outdoors.

The daily energy savings are around 13% in the summer and 9% in the winter. This level of energy saving is because, as compared to a building skin with glazing only, the dynamic skin system with its open device configuration can still allow entry of indirect daylight. The results shown that the moveable, tightly folded morphology, which enables parametric self-shading, is crucial to lower temperatures, allow daylight entry, and optimise energy use.

This research covers several subjects. It has only been possible to touch on each to develop a high-level interdisciplinary knowledge. Further research into multidisciplinary and interdisciplinary, kinetics, building interactions, the use of parametric design and more would ultimately enrich this research further. Ideally, all this research should be expanded by an interdisciplinary team of experts. There are many avenues for future research on both theoretical and practical levels:

- Verify the results obtained using physical prototypes.
- Investigate the application of biologically inspired materials, different morphologies and geometrical designs.
- Consider other research strategies. During the planning stages of this research, an alternative research method was considered that would test the acceptability of the concept to various relevant social groups using models for participants to observe. This research would highlight any preconceived notions people have about architecture that is adaptable, responsive, kinetic and/or transformable.
- Consider post occupancy analysis to understand how occupants react to such buildings and their performance effectiveness.
- Train designers further on computer modelling to help them understand the performance characteristics of different building skin strategies.
- Formulate a new vocabulary, develop a new type of construction method and describe a new aesthetic. Kinetic architecture has begun.
- Generate useful inputs such as life cycle assessments, business models and marketing strategies
- Develop monitoring-based benchmarks in order to inform the professional and research communities of requirements and needs for adaptive facade assessment.

Biographies

Sara Khelil

Department of Architecture, University of Biskra, Biskra, Algeria, sara.khelil@univ-biskra.dz, 00213558226702

Dr. Khelil is an Algerian associate professor, responsible for the Architecture Department at the University of Biskra. Her scientific interests focus on biomimicry, parametric design, daylight and energy efficiency. She is involved in many collaborative research projects. Dr. Khelil teaches undergraduate architecture courses and advanced courses for graduate students. She is a member of many international organisations and the leader in many environmental design and sustainable urban planning research projects. She is an authur of several journal papers and publications in indexed international conference proceedings. She participates in undergraduate and graduate thesis committees throughout the country. ORCID: 0000-0002-2098-2107

Alla Eddine Khelil

Escuela Técnica Superior de Arquitectura, University of Seville, Seville, Spain, khelilallaeddine@gmail.com, 00213558125010

Mr Khelil is an Algerian has an Architecture MA, obtained from the University of Biskra-Algeria and an Innovation in Architecture: Technology and Design MA from Escuela Técnica Superior de Arquitectura, University of Seville, Spain. He is a member of the research project 'The use of parametric design in urban design' supervised by Prof. Cubukcu Ebru from Dokuz Eylul University - Izmir Turkey. He is an author of several journal papers and publications in indexed international conference proceedings.

Tallal Abdel Karim Bouzir

Department of Architecture, Institute of Architecture and Urban Planning, Blida University, Blida, Algeria, bouzirtallal@gmail.com , 00213770596619

Dr. Bouzir is an Algerian associate professor at the Institute of Architecture and Urbanism of the University of Blida, Algeria. His areas of research interest cover urban planning, noise pollution, soundscape studies, urban morphology and environmental issues and architectural and urban atmospheres. He has a background in architecture and environmental sciences (MA and PhD). He is the author of several journal papers and publications in indexed international conference proceedings. ORCID: 0000-0002-1902-1800

Djihed Berkouk

Department of Architecture, University of Biskra, Biskra, Algeria, d.berkouk@univ-biskra.dz, 00213770720140

Dr. Berkouk is an Algerian associate professor at Biskra University, Algeria. His research interests include studying the relationship between the physical environment and space occupance, human comfort, temperature and lighting control, soundscape, noise pollution, and urban morphology. Berkouk regularly participates at international conferences, and he has contributed to research articles published in reputable national and international journals.

ORCID: 0000-0002-2925-3015

Noureddine Zemmouri

Department of Architecture, University of Biskra, Biskra, Algeria and Laboratory of Design and Modelling of Architectural and Urban Forms (LACOMOFA), Biskra, Algeria, noureddine.zemmouri@univ-biskra.dz, 00213550856373

Prof. Zemmouri is an Algerian professor, vice director responsible for

post-graduates and research, director of LaCoMoFa Laboratory, president of the scientific board and director of the graduate programme Building Science and Sustainability at the Department of Architecture. A Fulbright programme visiting professor at the MBS programme at the University of Southern California School of Architecture in Los Angeles USA, and a distinguished speaker at the Graduate School of Human Environment Studies, Kyushu University Japan. ORCID: 0000-0001-8400-5690

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