CLIMATE ADAPTIVE BUILDING SHELLS FOR OFFICE BUILDINGS IN EGYPT: A PARAMETRIC AND ALGORITHMIC DAYLIGHT TOOL

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Abstract

There is an emerging need to include sustainability–related performance features within the conceptual design stages of a building, especially for parameters such as daylighting and energy usage. Advances in digital architectural design now mean there are innovative possibilities for designing and evaluating dynamic façades capable of generating predetermined environmental performance criteria within a space. It is possible to update the traditional concept of the building envelope from acting not as a passive barrier but as an active negotiator with the surrounding environment. A framework is introduced in which the interdisciplinary integration and performance optimization of climate adaptive building shells (CABS), inspired by traditional Egyptian patterns, were synthesized to evaluate a wide range of façade design alternatives. A multi-objective optimization model for shape exploration is presented to assist designers in creating performance-driven forms at the early design stages. Daylighting was the key performance criterion used to design a CABS system using parametric design and optimization tools for an office space in Cairo, Egypt. The results demonstrated that the CABS system could achieve the desired daylight criteria using its own predefined capabilities.

Keywords: CABS (Climate Adaptive Building Shells), daylighting, performative design, genetic algorithms.

1 INTRODUCTION

According to the United States Energy Information Administration (EIA), almost 40% of total energy consumption in 2012 was by the residential and commercial sectors in the U.S [1]. Consequently, architects have a responsibility to search for ways to reduce energy consumption without affecting the building user's comfort. One of the possible ways to achieve this target is by controlling the daylighting that enters the building through its envelope to improve indoor environment, while reducing the energy consumed by artificial lighting, cooling and heating loads [2][3]. In addition, daylight and sunlight are significant for health and well-being. Recent studies have emphasized the need for more interesting work place environments, with the benefit of improved productivity [4]. However, sunlight needs to be controlled in terms of sufficiency vs. excess in order to satisfy the occupant's comfort requirements. This is especially true for a climate such as Egypt's, which is characterized by high direct solar radiation and clear skies [5]. This climate's sky conditions could contribute greatly to the utilization of daylighting. On the other hand, this climate may also cause excessive heat gain or visual discomfort [6]. All these facts highlight the need of updating the traditional approaches of the building envelope from acting only as a passive barrier towards a building envelope which acts as an active negotiator with the surrounding environment.

Climate Adaptive Building Shells (CABS) is an example of this updated approaches. CABS have the ability to dynamically control the exchange of energy through a building's shell over time in response to the meteorological conditions and occupants' requirements; this attitude affords many gains such as energy saving and higher performance's recognition [7]. CABS is one title for a concept that has been branded by a range of terms, such as *interactive* [8], *responsive* [9] and *smart* [10]. The integration of daylighting performance into the conceptual phase of designing, using CABS for an office building in Cairo, is examined in this study.

2 PERFORMATIVE ARCHITECTURE

Integrating performance-based approach in the early conceptual design stage is significant to achieve innovation and efficiency. A parametric model can become a controlled environment for design exploration in which the search for a fitter design alternative according to pre-defined fitness criteria can be easily carried out [11]. A carefully designed CABS system can provide energy savings and indoor comfort [12,13], for example, the façade design of the Arab World Institute (AWI) in Paris by Jean Nouvel (Fig.1) and Aedas Architects' Al Bahar Towers in Abu Dhabi (Fig. 2), with a responsive facade inspired by the '*mashrabiya*', a traditional Islamic lattice shading device (Fig.2).

Figure 1. AWI kinetic façade system.

Figure 2. Al Bahar Towers

In this study a CABS building facade to enhance daylighting performance in a Cairo office building has been tested. The CABS façade pattern was inspired by projects of the famous Egyptian architects Hassan Fathy. The use of claustra is one of Fathy's most characteristic visual elements, and relates to an urban precedent in the wooden lattice windows (mashrabiya) of houses in old Cairo [14].Hassan Fathy used Claustra as shading devices to permit diffuse light, prevent direct sunlight, and control glare (Fig.3).

Figure 3. The use of claustra by Fathy

3 METHODOLOGY

Using parametric design a three dimensional geometric façade configuration, inspired by traditional Egyptian claustra and mashrabiya, was developed and integrated with horizontal and vertical louvers system that are proposed as a CABS outer skin for the aerated. Focussing on a south facing office space in Cairo a CABS system was developed aiming to enhance the indoor daylight quality at 12.00 pm on the 21st March (vernal equinox); 21st June (summer solstice); 21st September (autumnal equinox)) and 21st December (winter solstice). An algorithm was employed in this parametric study to examine the advantages of using CABS system for improving the daylighting performance in office spaces. The flexibility of the parametric model provided a wide variety of shapes and sizes of folds, and sizes of openings. With the help of the evolutionary solver, a balance was found among these variables that minimised heat gain whilst also providing adequate daylight for the occupants. The idea was to design CABS system consisting of 40 units each unit 1m * 1m and they were randomly divided into 4 groups each having different scale based on 30 different random distribution scenarios for a south facing façade inspired by traditional Egyptian pattern (see Figure 6) which have the capability to change its configurations in response to the surrounding environment based on a desired predefined design criteria. The whole system could be fully closed when daylight is not favourable or fully opened when daylight is favourable. Figures 4, 5, 6 and 7 show the development of the CABS system with louvers.

Figure 4. Extracting the concept of the designed pattern.

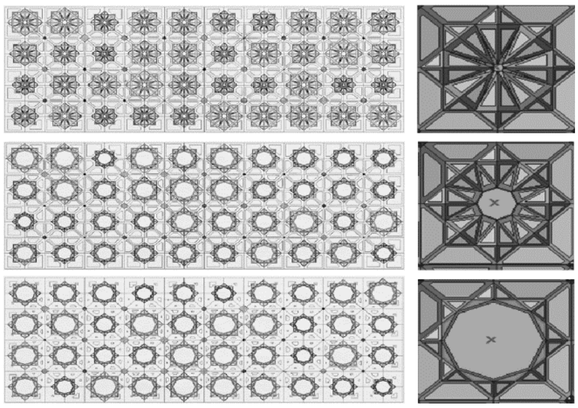


Figure 5. CABS system opening ratios ranging from 10% to 90%

Figure 6. Shows the random distribution of the system's groups.

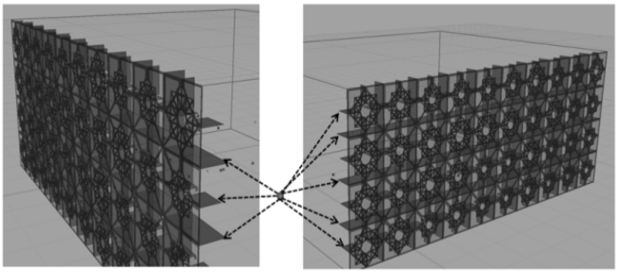


Figure 7. Integration of louvers with pattern.

3.1 Daylight Design Criteria

This paper considered five indicators (illuminance, illuminance contrast ratio, daylight depth, glare and solar irradiation), based on the recommended office illumination levels from the Illuminating Engineering Society of North America (IESNA). [15]; the NRC Institute for Research in Construction [16]; and the European Standard for Light and Lighting for Indoor Work Spaces [17]. The study was applied in three main phases. The first phase was concerned with daylighting adequacy, ensuring that all work planes received a minimum of 500 lux and a maximum of 2000 lux, while reducing excessive direct sunlight penetration. The second phase was concerned with daylight distribution and all the selected alternatives had to ensure that at least 80% of the total office space area was daylit at the four required times of the year representing the four seasons to ensure visual comfort during the entire year. Three zones described the space as being either 'daylit' (illuminance levels between 300 and 3000 lux); 'partially daylit' (less than the minimum illuminance of 300 lux) and 'over lit' (daylight illuminance exceeds the maximum illuminance of 3000 lux). The 'over lit' area signifies the potential for heat gain and glare risk [18] [19]. The third phase investigated all the selected alternatives to ensure visual comfort inside the space. A point-in-time glare simulation using DIVA software was carried out at a height 1.3m (sitting position and looking towards the widow). The Daylight Glare Probability (DGP) metric was used in the visual comfort evaluation which considers the overall brightness of the view, position of 'glare' sources and visual contrast. DIVA is an environmental analysis plugin for Rhino that uses Evalglare to calculate DGP from a luminance image based on total vertical eye illuminance and contrast [19]. Glare was considered being intolerable if DGP >45%, disturbing when it is between 40% and 45%, perceptible when it is between 40% and 35%, and imperceptible when it is less than 35%. To summarise, the study was seeking to design a CABS system to fulfil the criteria in outlined in Table 1.

A generic south-facing office 10m x 8m x 4m high, located in Cairo, was selected for this study with no external obstructions. Such an office can hold 9 workstations. The office space and CABS system were modelled using Grasshopper for Rhinoceros. The recognition of and CABS geometry were constructed in the multiple parameters that control the surface.

Table 1. Criteria

Indicator	Illuminance
Target for working plane	Min of 500 lux, max of 2000 lux and at least 80 % of the rest of the space between 300 lux and 3000 lux.
Daylight depth	2X
illuminance contrast ratio	1:8
Glare	DGP<35%
Solar radiation	Minimum

The parameters of the office space and CABS system configurations are illustrated in [Tables 2 and 3]. The CABS system consist of a parametrically designed pattern integrated with horizontal and vertical louvers; the system was controlled by 17 parameters to insure adequate daylight in term of quantity and quality for the four required times all the parameters are fixed except eight parameters.

All variables were governed automatically through the algorithms to start generating the permutations were based on the daylight and solar radiation simulation results.

Table 2. Model and CABS parameters

Space Parameters	
Walls	Reflectance = 50%
Ceiling	Reflectance = 90%
Floor	Reflectance = 20%
CABS	Reflectance = Metal diffuse for façade's frames and Glazing_DoublePane_LowE_65 for glazing

Table 3. CABS Parameters

No	Parameters	Possible Values
1	Pattern's random distribution	30 random distribution's scenarios with different scales.
2	Main pattern opening ratio	10, 20, 30, 40, 50, 60 , 70,80 and 90 %
3	Hex opening diameter	100, 200, 300, 400 and 500 mm
4	Main Horizontal and vertical Louvers Rotation	-75°, -60°, -45°, -30°, -15°, 0°, 15°, 30°, 45°, 60° and 75°
5	Secondary Horizontal and vertical Louvers Rotation	-75°, -60°, -45°, -30°, -15°, 0°, 15°, 30°, 45°, 60° and 75°
6	Louvers Depth main and secondary louvers	100, 200, 300, 400 and 500 mm
7	Background opening ratio (four groups)	10, 20, 30, 40, 50, 60 , 70,80 and 90 %
8	Pattern extrusion	100, 150, 200, 250, 300 mm

3.2 Simulation Parameters and Procedure

CABS must respond to particular environmental conditions at its location. For the purpose of this case study, Cairo (30° 2' N, 31° 14' E) and its weather file (Cairo Intl Airport 623660 (ETMY)) were used for the analysis [20].

3.3 CABS System Configurations

The tool was developed as a parametric model in which variable geometries are defined with associated constraints. The 3D model and components were then actuated through the algorithm simulating intelligently evaluated independent CABS system configurations. The design of the CABS originated in Grasshopper. All variables for CABS alterations were defined; the CABS geometry was connected to the daylighting analysis component DIVA, which uses Radiance as the daylighting calculation engine. DIVA plugin for the Rhinoceros and Grasshopper environment supports a series of performance evaluations by using validated tools including RADIANCE, Daysim, Evalglare and Energy Plus software. DIVA performs a daylight analysis on an existing architectural model via integration with Radiance and Daysim [18]. This method allows the rapid visualization of the daylight and energy consequences of an architectural design model where multiple design variants for daylight and energy performance can be easily tested without manually exporting to multiple softwares. DIVA was chosen so that all modelling and daylight simulations could be carried out within the Rhino and Grasshopper environments for the prediction of various radiant or illuminance calculations using sun and sky conditions derived from standard meteorological datasets.

The results are dependent both on the building location and orientation, in addition to the CABS composition and configuration. Two groups of nodes were generated – the first being a horizontal group for the illuminance measurements, located 0.76m above the floor, consisting of seventeen points representing the nine workstation locations and eight points to provide an indication of adequate daylight depth (Fig.8).

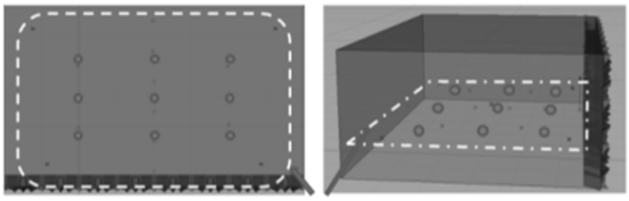


Figure 8. Measuring nodes for illuminance

The second group was a vertical grid for the south façade's solar radiation calculation located 200mm inside the space, just behind the CABS system, to measure solar radiation which had passed through the CABS; this involved 40 points covering 100% of the glazing area distributed as one point for each m^2 of glazing. (Fig.9). All surfaces, materials and nodes were defined and linked to the DIVA plug-in for both Illuminance and solar radiation analysis.

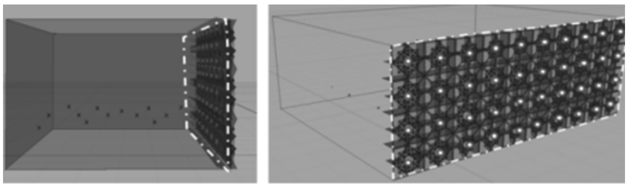


Figure 9. Measuring nodes for radiation

The overall definition of a solution generated in Grasshopper can be divided into five distinct groups: model geometry, folded façade, performance simulation, optimization and data recording. All results are examined simultaneously by evaluation functions of the algorithm and filtered based on the predefined criteria. The algorithm evaluated the space for three particular criteria: (i) 100 % of the nine nodes on the working plane are within the desired illuminance range (500-2000 lux); (ii) the illuminance contrast ratio in terms of contrast ratio between highest and lowest node values exceeds 1:8 and (iii) 100 % of the eight tested nodes (out of the working plane) are with the range 300-3000 lux. All values are then sent to the genetic algorithm. The main objective of the study was to achieve all seventeen calculation points being within the range of acceptable illuminance values.

At the same time as results were evaluated for illumination levels, another function of the algorithm was testing the results for illuminance contrast ratio evaluation. Since the illuminance values had been sorted in a descending order, the highest point will have an index of ‘0’ and the lowest value will have an index of ’16’. Both values were extracted using the ‘list item’ component and divided by each other. If the result is within 1:8 ratios for contrast ratio, the solution is considered acceptable and sent for solar radiation calculation (40 vertical measuring nodes); otherwise, it is considered unacceptable and neglected.

For the purpose of optimization Galapagos is used, which is a genetic algorithm imbedded in Grasshopper and running in Grasshopper through the Rhino interface. By using Galapagos a wide range of alternatives can be explored and evaluated, basically, evolutionary computing works by giving each variable, or gene, an assigned fitness value, then iterates through different mutations of genes with the optimized solutions surviving, every iteration plays an important role in the way the genes combine.

In this step, the architect determines the suitable optimization algorithm and the heuristic algorithm will manage the flow of parameters and performances between the simulation and the modelling software, the algorithm takes the parameters of the CABS with their performance from the simulation program.

Then, based on the rule governing the selection of the optimum solution (parameters), the algorithm starts sending new parameters to the simulation program and receives the results and the previous steps are iterated until the optimum solution is reached.

Galapagos has been integrated to search for the best CABS configuration at specific dates and times. The genetic algorithm works on finding an optimal solution that fits the predefined criteria. Galapagos works on minimizing the solar radiation for the successful solutions. The algorithm operates by randomly generating numerous CABS configuration, evaluating a different combination each time, and TT-Toolbox is used for data recording. Finally, a group of CABS configurations that maximize the quality of daylighting within the predefined criteria and have the minimum solar radiation value as desired was reached.

All the optimum groups of solutions (population) were examined and compared architecturally. For results verification, four successful solutions were selected as optimum solutions (one solution for each of the following times: 12.00 pm on the 21st March (vernal equinox); 21st June (summer solstice); 21st September (autumnal equinox)) and 21st December (winter solstice). Advanced simulation and data verification were carried out in two main stages:

Stage 1: In order to verify the results, successful solutions were compared twice using DIVA for Grasshopper for the same conditions (material, space dimension, weather file and time, etc) with:

- A base model without CABS.
- Alternative with lower fitness value.

Stage 2: Advanced simulation carried out for all the space using DIVA for Rhino, which has more capabilities for results’ verification and in-depth analysis.

Optimum solutions for all of the times were selected, then a point in time illuminance analysis was carried out to examine the daylight adequacy of all the space by measuring the illuminance values of nodes for a grid spacing of 0.42 m (190 nodes) to make sure that at least 80% of the space received illuminance between 300 lux and 3000 lux, and for glare probability to make sure that the users didn't receive intolerable glare (DGP > 45%). All simulations were carried out using DIVA for Rhino for results verification and compared with a Base model without CABS using the same conditions (material, space dimension, weather file and time) to examine: (i) Point in time illuminance and (ii) Point in time glare probability.

4 RESULTS

The optimised CABS systems were compared to the base model without CABS system in two phases. The first phase considered illuminance, luminous distribution and solar irradiation and the second phase daylight glare probability (DGP). Examples of some of the results are described below.

4.1 First phase: illuminance, illuminance contrast ratio, daylight depth and solar irradiation.

Table 4 shows graphically the daylight illuminance distributions for the dates/times investigated with and without the optimized CABS. The large dark coloured areas in the 'without CABS' office represent illuminance levels greater than 3000 or less than 300 lux (over lit and partially lit areas) whereas the light coloured areas, indicating values between 300 lux and 3000 lux.

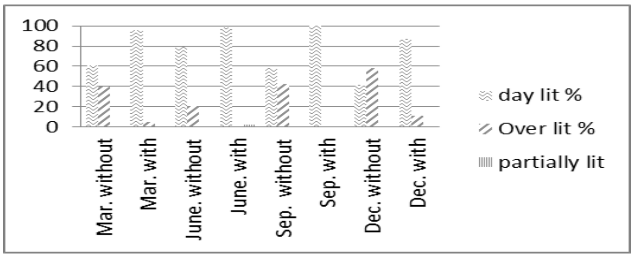
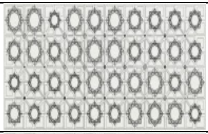
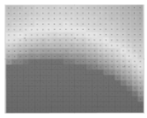
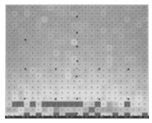
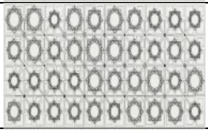
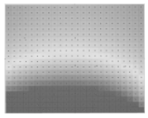
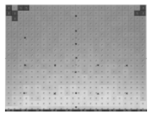
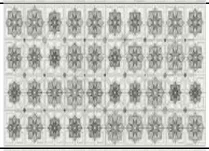
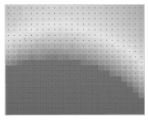
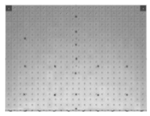
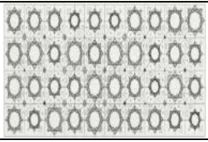
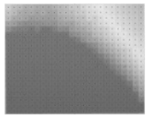
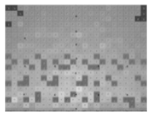


Figure 10. Daylighting performance with and without CABS

Table 4. The daylighting performance with and without the optimized CABS.

Date	Façade Design	Without CABS	With CABS
Mar. 21st			
June 21st			
Sep. 21st			
Dec. 21st			

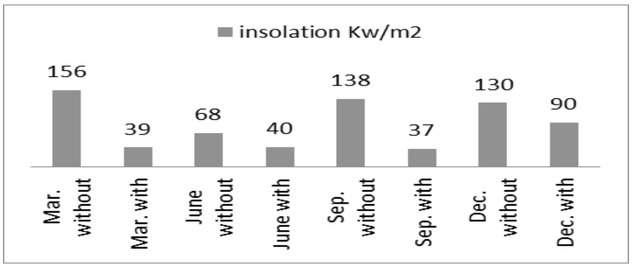


Figure 11. Solar Irradiation with and without CABS

4.2 Second phase: Daylight Glare Probability (DGP).

A point-in-time glare simulation in DIVA was carried out and the visual comfort of a person under the simulation conditions at the camera viewpoint examined.

An annual glare simulation was undertaken for the office without CABS with hourly calculation (Fig. 12)

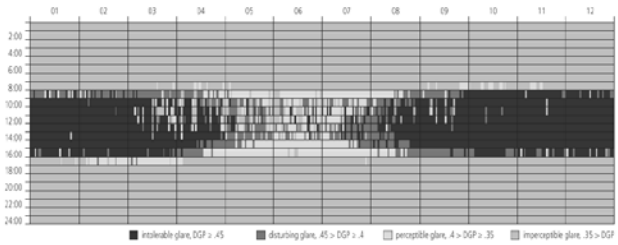


Figure 12. Temporal Maps of Annual DGP Throughout the Day Without CABS

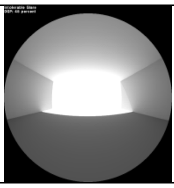
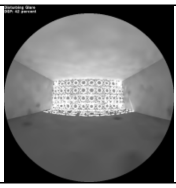
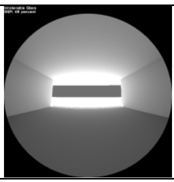
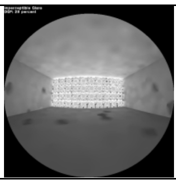
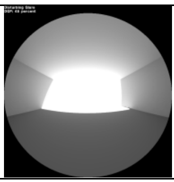
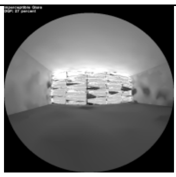
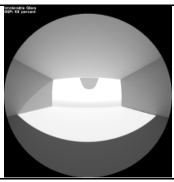
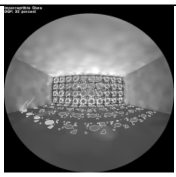
- The annual DGP throughout the day without CABS shows that the examined point received an intolerable glare > 45 within the working hours (from 8 am to 4 pm) during the year especially in the winter season.

Results from point in time DGP calculations for a point in the middle of the office space at a height of 1.3m above the floor (sitting position and looking towards the widow) with the optimized CABS at the four examined times are described below.

- The results with the optimised CABS system indicted that the examined point received an Imperceptible glare (which fillfull the design criteria) at all the examined times except at March it received a disturbing glare. (See table 5)

Table 5 presents graphically the results of point in time glare for the optimised CABS (21st of March, June, September and December at 12.00pm).

Table 5: Percentage of Daylight Glare Probability (DGP) for each scenario.

Time	Without CABS	With CABS
March 21st		
	Intolerable glare 46%	Disturbing glare 41%
June 21st		
	Intolerable glare 46%	Imperceptible glare 29%
Sep. 21st		
	Disturbing glare 45%	Imperceptible glare 28%
Dec. 21st		
	Intolerable glare 63%	Imperceptible glare 32%

5 CONCLUSION

This paper demonstrates a CABS system governed by daylight performance criteria. The system has been tested through integrating daylighting simulation tools and genetic optimization with a parametric facade model inspired by the works of Egyptian architect Hassan Fathy. The simulations were conducted for a south facing façade of an office space in Cairo, Egypt. Several CABS parameters were modelled to be used for the optimization process. The CABS system's capabilities were examined during the specified four times and proved its capacity of providing an adequate daylighting performance that fulfilled the required criteria using its predefined configurations and capabilities. The results proved that integrating daylighting simulation tools and a genetic algorithm to drive parametric façade designs can contribute in reaching better daylighting performance. In the future this study will be extended to consider the parametric optimization of façade designs in terms of thermal loads and occupant thermal comfort.

In conclusion, this study has demonstrated that a CABS system with a complex geometry can be successfully modelled, tested and capable of satisfying the desire of combining aesthetic values, building performance and user comfort in office buildings.

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