TOWARDS A SOLUTION FOR THE INEVITABLE USE OF GLAZED FACADES IN THE ARID REGIONS VIA A PARAMETRIC DESIGN APPROACH

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Abstract

The utilisation preference of glazed facades in the hot regions is accompanied by serious environmental and economic impacts. Attempts are continuing to fulfil an optimum balance between minimising heat gains and maximising daylighting benefits; in an economical approach. This study was conducted in Egypt, where a real case study was investigated to evaluate the thermo-visual performance of a building with glazed facades. Improvements of the thermo-visual performance are pursued via the application of five different glazing alternatives in the first phase of the study. In the other two phases, further enhancement is sought via the addition of parametric lightshelves and perforated double skin facades; creating a total of 138 possible configurations. The best configuration that combined clear glass and a lightshelf has significantly improved the thermal comfort and daylighting uniformity, but it also slightly improved the availability of daylight. This ultimately leads to an energy saving, however, further economic assessment is required.

Keywords: Glazed facade, Arid region, Parametric design, Thermo-visual performance

1 Introduction

The increasing preference to use glazed facades in office and public buildings, regardless of the geographical location or climatic region, is a major contributor towards the influence of thermo-visual comfort. Additionally, that leads to an increasing reliance on mechanical air conditioning systems, and the consequential increase in electricity consumption and CO2 emissions. To decrease all of these disadvantages, efforts have been split into two approaches. The first seeks to limit the utilisation of glazed facades in arid regions, and encourages local techniques to control the internal environment. However, that comes against the desire of a significant number of building designers and developers who would like to obtain the architectural appeal and modern appearance of glazed facades. As a result, the second approach emerges. It resorts to the use of intelligent facade systems, which are considered a multiple functional element to reconcile the conflicting needs such as lighting, heating and cooling. Double skin facades and smart windows are examples of these systems.

The design and evaluation of the glazed facades are influenced by many aspects, such as orientation, size and glass type. Each of them has a different influence on visual, thermal, environmental and economic performances. Knowing the best performance combination is challenging without the aid of the recently developed simulation software that enables the assessment of a huge number of glazed facade configurations. This parametric environment allows for the manipulation of different configurations by changing pre-set parameters to produce different solutions within each configuration. This process facilitates the testing of all of the possible configurations in order to identify the best performing solution in terms of lighting, heating, cooling and energy consumptions (Linhart, Wittkopf, & Scartezzini, 2010; Verso, Serra, Giovannini, & Iennarella, 2014).

This work aims to introduce a set of parametrically tested, optimised glazed facades that can greatly improve existing daylighting conditions in office buildings with glazed facades in hot arid climates, and increase the occupants comfort by reducing solar heat gain that is undesirable in such climates, and ultimately reduce energy consumption.

2 Overview of glazed facades

To enhance the thermo-visual performance of glazed facades, attempts have been done to control the solar and visible light transmittance through the glass. Although solar control glass has been produced to minimise the need for mechanical cooling systems and to eliminate visual disturbance factors, this strategy proved to be insufficient in the arid climatic regions. Other approaches have been applied or investigated, such as the addition of solar control devices, the use of multi-layer facades or the engagement of smart windows.

The double skin facade is essentially a pair of glass skins separated by an air corridor, which works as insulation against temperature extremes and sound. Every type of double skin facade offers a protected place, within the air gap, to mount shading and daylight enhancing devices. On the other hand, some problems could arise, such as overheating in summer seasons, higher investment costs, reduced building floor space and additional cleaning costs. Double skin facades are mostly used inside central Europe, principally because energy prices are significantly higher in Europe than in other places, resulting in a faster return on investment (Poirazis, 2004). There has been very limited research on the thermal performance of double skin facades in hot arid areas, and these studies were solely based on simulation that showed that better energy saving can be achieved using a double skin facade rather than a single skin (Baldinelli, 2009; Cetiner & Özkan, 2005; Hamza, 2008) or a multi-layer climate interactive facade system (Radhi, Sharples, & Fikiry, 2013). However, the economic factors need further investigation.

The application of smart windows that employ electrochromic glass may lead towards the reduction of energy consumption and control the visual environment. The electrochromic glass optical transmittance can be controlled, since they can be darkened or made lighter to adjust the light permitted to enter the space. However, without the aid of shading devices, electrochromic window cannot provide visual comfort in extreme glare situations on their own (Fernandes, Lee, & Ward, 2013). For practical application, the smart windows have to satisfy three criteria: a high transmittance modulation range in the visible and whole solar spectrum, long lifetime without significant degradation and acceptable switching time for colouration (Baetens, Jelle, & Gustavsen, 2010).

3 Study methodology

New Cairo, a newly developed urban settlement around Cairo (30° N, 31° E), the capital of Egypt, has been selected as a study area due to its popularity and fast growing ratio. A field survey has been conducted over a sector of the main commercial spine to study the forms and types of the buildings' facades. Then they have been classified according to the extent of the employment of the glass in the main facade, in terms of glass-to-facade ratio. In addition, the used external shading devices have been determined.

An office building, representing the study area, was examined to measure the existing thermo-visual performance. A number of facade alternatives have been examined in order to obtain a better performance. In the first phase, a more efficient glass has been examined. In the second phase, lightshelves have been added. Then, in the third phase, a second layer of perforated facade has been applied. For the last two phases, a parametrical design has been applied to achieve the best thermo-visual performance.

The selected case study has been modelled in Grasshopper, a visual programming parametric modelling environment for Rhinoceros (McNeel, 2010). Later, various sets of parameters are modelled within the case study. Changing those parameters results in the creation of multiple configurations. Daylighting performance as well as thermal analysis for each configuration is evaluated for a fixed analysis grid that is placed 1 metre from the floor and contains 312 sensor points. Performance analysis simulations were performed using a brute-force algorithm. As a straightforward approach to problem solving, a brute-force solver will generate all possible parameter combinations (Rosen, 2011) and solve the definition of each combination, allowing for the exploration of all of the configurations within a parametric model. Honeybee and Ladybug, environmental analysis Grasshopper plug-ins, are used for calculating various daylighting and thermal comfort indices (Roudsari, Pak, & Smith, 2013).

Radiance engine is called by Honeybee to perform daylighting simulations. Its ambient bounces setting was fixed to 4 (-ab).

Quantitative daylighting performance analysis for each configuration was performed, and useful daylight illuminance (UDI) was chosen to measure daylight availability over the analysis grid sensors. UDI is a modification of the climate based metric Daylight Autonomy (DA). UDI was first developed on 2005 by Mardaljevic and Nabil (Nabil & Mardaljevic, 2005). This metric considers only illuminance values between 100 lux and 2000 lux, suggesting that horizontal illumination values higher than 2,000 lux are not useful due to potential glare or overheating, and values lower than 100 lux are poorly lit.

A qualitative analysis for each parametric iteration was measured and expressed in a lighting uniformity ratio (LUR), which is the ratio of the minimum illuminance to the average illuminance as suggested by the Illuminating Engineering Society of North America (DiLaura & America, 2011). The aim is to distribute light across the room with a ratio of 1:3 or better. LUR was calculated on the summer solstice, June 21 at 09:00, when low elevation sunlight penetrates the interior space causing bright patches of bright sunlight that ultimately cause glare.

Giving its strong influence on thermo-physiological comfort indices such as physiological equivalent temperature or predicted mean vote (Fanger, 1970), Mean Radiant Temperature (MRT) was adopted in this study as a measure for the thermal performance for all of the parametric iterations that are evaluated. The average MRT was calculated based on the MRT values measured at all 311 sensors in the analysis grid on the summer solstice, June 21st at 12:00 O'clock. The thermal simulation program Energyplus is called by Honeybee for a thermal performance analysis.

In search for a feasible configuration with the highest daylighting and thermal performance, simulation results are ranked using multiple criteria decision analysis (MCDA) methods, which have been utilised recently in the context of high performance building design (Mela, Tiainen, & Heinisuo, 2012).

4 The case study: Glazed facade utilisation and evaluation

4.1 Definition of the study area

According to Köppen-Geiger's climate classification, New Cairo falls into the hot arid desert climatic region (KOTTEK, GRIESER, BECK, RUDOLF, & RUBEL, 2006). A 21-year average of the annual sum of the global horizontal irradiance is about 1800 kWh/m2, and the global horizontal irradiance is 205 W/m2 (SoDa, 2011). The annual average external illuminance is 22.8klux, which is derived from the global horizontal irradiance; using a luminous efficacy value of 111.4lm/W (Mayhoub & Carter, 2011). Cairo is very sunny with an 18% average cloud cover, and there are absolutely no clouds in sight almost half of the time. The median daily cloud cover ranges from 19% to 49%, based on the historical data from 2006 to 2012 that was recorded by the Cairo International Airport weather station.

New Cairo was selected as it can be considered to be the most attractive area for new constructions in the Cairo metropolitan area over the last decade. The study area is a linear raw of buildings that extends about 3 km along the southern 90th Street, which is the most important street in the city. A considerable number of corporations and institutions have recently established new headquarters or main branches in the commercial spine. Most of these buildings' facades include vast areas of glass, with different ratios, characteristics and added shading devices (Fig. 1).

4.2 Current status of the glazed facade in the study area

The study area consists of 26 buildings, but only 23 of them have been completely constructed. The allowed height is about 25m. The buildings have been classified into three groups according to the percentage of glass area in the main facade that faces a southern direction. The first group includes four buildings (17%) out of 23, with a glass component that represents less than 40% of the main facade. The second group includes seven buildings (30%); in each of these the glass represents from 40% to 80% of the main facade. In the remaining 12 buildings (53%), more than 80% of their main facade is covered by glass (Fig. 1).

The visually recognisable characteristics of the glazed facade can only be determined, such as its colour, the number of glass layers and the shading devices that are attached. Meanwhile, some characteristics such as the solar and visible light transmittance and reflectance are unavailable. Different glass colours/tints are used, such as silver, grey, blue and green, in addition to clear and reflective glass. In only four cases (17%), shading devices have been used, louvers in three cases and lightshelves in one.

Figure 1 – Samples of the three categories of glazed facades in the study area

4.3 Estimation of the current glazed facade performance

Figure 2 illustrates the office building that has been used to estimate a sample of the current performance. The glass covers about 64% of the main facade, with no shading devices, apart from small lightshelves between the floors for aesthetic purposes. Since this is the southern facade, internal manual controlled blinds have been used to avoid direct sunray penetration or to limit excessive illumination within the perimeter zone. The typical floor plan was designed as an open office area. The distance between the building envelope and building core exceeds 12m in all directions. Additional vast areas of glass exist in all the other facades.

One typical floor is modelled in a parametric environment. The clear ceiling height is 3m. The floor, ceiling and wall reflectance are 80%, 20%, and 50% respectively. A Large blue-tinted glazing curtain wall is facing south, other considerably large areas of blue-tinted glazing face east and west, and about 20% of the north facade is glazed. All glazed areas in the selected case study were modelled using double 8mm blue-tinted panels with a 16 mm argon filled cavity. The glazing system's solar transmittance and reflectance are set to 19% and 35% respectively. Its visible transmittance and reflectance were set to 51% and 14% respectively. Any shading from adjacent buildings was accounted for in both daylighting and thermal simulations.

An initial performance simulation was conducted to evaluate the base case performance. The simulation results showed that the base case's average UDI equalled 84.17 %, while the LUR is equal to 0.23 and the MRT is 31.18 °C.

Figure 2 – The case study building facade, typical floor plan and aerial view

5 Enhancement of the glazed facade performance

Selection of the right glazing is of major importance for improving the building's thermos-visual performance and energy consumption. In search of improving the base case's performance, daylighting and thermal performance simulations are performed for the case study with five different types of glazing that have solar transmittance values ranging from 10% to 65%, and visible transmittance values ranging from 18% to 80%. Some of the selected glazing materials have a high reflectance coating that can help to reflect sunrays and prevent overheating. Full glazing properties are listed in table 1. All of the tested glazing systems are 8mm double panels with a 16mm argon-filled cavity.

Table 1 – Glass visible and solar transmittance and reflectance values

Glazing material	Visible transmittance	Visible reflectance	Solar transmittance	Solar reflectance
Ultra-clear	80%	12%	62%	21%
Clear	43%	27%	15%	42%
Light grey	37%	9%	14%	17%
Silver grey	22%	11%	10%	19%
Silver	18%	31%	13%	27%

Many studies have shown that high reflective light shelves are beneficial for increasing light levels in areas that are far from the window by reflecting sunlight into the back of the room, thus, improving light distribution and uniformity (Labib, 2015) (Freewan, Shao, & Riffat, 2008). Additionally lightshelves are useful for shading primarily with windows that have large glazing areas and heights that are greater than 2.2 m (Wulfinghoff, 1999). Therefore, in phase II, an exterior parametric lightshelf was modelled, and its thermos-visual performance was evaluated. Controlling the lightshelf parametrically allowed for 16 possible configurations. The parameters include the lightshelf distance from floor, depth, form and material, as summarised in Table 2. All of the lightshelf configurations were tested with the base case glazing system and the additional 5 glazing systems that were examined in phase I, thus, the total possible configurations in phase II increased to 96 possible configurations.

Various research studies have confirmed the positive impact of using double facades in building retrofit to improve the building daylighting, thermal and acoustics performance (Gibbs & Hammad, 1985) (Etman, Tolba, & Ezzeldin, 2013). In the third phase of this study, a parametric perforated facade and its thermos-visual performance is assessed. Changing the various parameters in the facade's opening leads to three possible configurations with different opening to wall ratios of 15%, 30% and 40%. In addition to the opaque perforated facade, a glass one with a low transmittance value of 20% is modelled and tested. All perforated facade configurations were evaluated with the glazing system combinations examined in phase I, this leads to an increase in the number of possible configurations in this phase to 36 (Table 2).

Table 2 – Parameters and variables used for daylighting and thermal performance simulations

Phase	Parameters	Suggested configurations
Lightshelf	Height from floor	2m, 2.5m
	Lightshelf depth	0.5m, 1m
	Lightshelf form	Flat, curved
	Light shelf material	Opaque (reflectance = 80%), glass (VT=20%)
Perforated facade	Facade material	Opaque wall, glass with 20% VT
	Openings to wall ratio	15%, 30%, 40%

6 Analysis and discussion of the glazed facade performance

Although the first phase daylighting simulations showed that the base case glazing yield the best UDI values, where the average UDI is 84.17%, on the other hand it showed a poor lighting uniformity ratio and thermal performance, where the LUR is 0.23 and the average MRT is 31.18 °C. Similarly clear and ultra-clear glazing showed high daylighting performance and poor lighting distribution and thermal performance where their average UDI, LUR and MRT are 77.78 %, 0.24, 30.4 °C and 32.8 %, 0.23, 32.8 °C respectively. Light grey glazing showed a balanced performance, while silver grey and silver glazing showed poor daylighting and thermal performance. (Figure 3). It was determined that replacing the base case glazing alone improves lighting availability but doesn't contribute to reducing the indoor temperature and distributing the light evenly to improve the occupants' visual comfort.

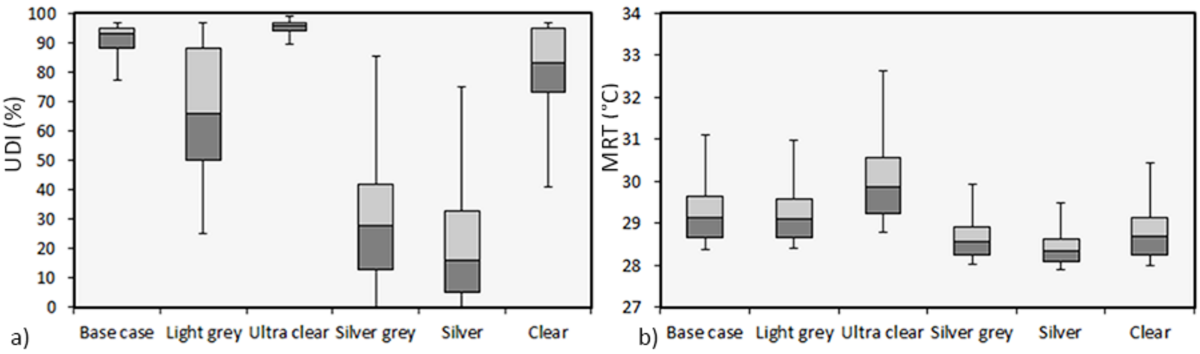

Figure 3 – a) Box plot graph of UDI values on the analysis grid sensors for various glazing materials. b) Box plot graph of MRT values on the analysis grid sensors on June 21 at 12:00 for various glazing materials

The results of phase II and III confirmed that a combination of a glazed facade, with a fairly high visible transmission value, and a shading device contributed to a better thermal performance in the examined office building. Furthermore, it led to a considerable improvement in daylighting distribution and availability. In a search for optimised solutions among the 138 configurations evaluated in this work, Multiple Criteria Decision Analysis Methods are used. The multi-criteria optimisation methods generate multiple optimised solutions, rather than searching for a single solution, to facilitate decision making.

To better analyse the simulations results, the weighted sum method (WSM) is used. It is a method that ranks multiple alternatives based on weights given by the decision making team, which in this case of facade retrofit can consist of many parties: owner, tenants, architects and consultants from various fields. Each criterion is given a non-negative weight, and the alternatives are ranked by evaluating the weighted sum of the criteria (Fishburn, 1967). WSM can only be used if the dimensions of the criteria don't differ from each other and if there is a wide range in their numerical values. To find the most optimum solutions a criterion based on the weighted sum of the examined criteria; daylight availability, daylighting uniformity and thermal comfort. However, these criteria have different numerical values and their range differs greatly, for example UDI values range from 0 to 100 and LUR values range from 0.22 to 0.39. To avoid this problem UDI, LUR and MRT values are normalised to score values between 1 and 138 based on their ranking in an ascending order. Because feasible solutions will have the lowest MRT values a reciprocal of MRT is adopted for the purpose of the normalisation process. Subsequently, high performance configurations are determined based on the sum of their scores in all of the three criteria using the following equation:

$$A_i^{\text{WSM-score}} = \sum_{j=1}^{n} w_j a_{ij} \qquad (1)$$

Where

$A_i^{\text{WSM-score}}$ is the sum of UDI, LUR, and MRT scores;

w_j is the weight of each criterion which is fixed at 1 for the purpose of this study;

a_{ij} is each criterion score.

Using the WSM method facilitated the determination of the feasible configurations that yield a high daylighting and thermal performance. Based on the WSM equation, the best configuration that scored the highest score (365) was determined to be the combination of an ultra-clear glazing and a 0.5 m depth, a high reflective opaque lightshelf placed at a 2.5m distance from the floor. This configuration increased the base case UDI and LUR from 84.17% and 0.22 to 89.50% and 0.39 respectively, while it decreased the average MRT from 31.2 °C to 26.1°C (Table 3). Meanwhile, the best-case scenario showed a slight improvement in daylighting availability, it showed a great improvement in both lighting distribution and thermal comfort. This leads to a significant reduction in cooling loads, and ultimately saves energy that is much appreciated, especially in Egypt where a recent study has shown that the country's demand for electricity is estimated to increase significantly, at a rate of 8% over the next few years (Hanna, 2011).

Looking at table 3, it is obvious that using the silver, light grey and silver grey glazing materials scored the lowest due to their low visible transmittance values that caused a significant decrease in UDI. Additionally, they contributed to an increased indoor temperature, although they have considerably low solar transmittance values between 10% and 14%. Perhaps this is caused by the lack of a shading device to prevent direct sunlight from entering interior spaces. UDI and MRT maps of base case and cases with the highest and lowest performances are illustrated in Figure 4.

Table 3 – Configurations with highest and lowest daylighting and thermal performance based on total ranking scores

	Configuration	UDI %	LUR	MRT ºC	Score
Best cases	Ultra-clear glazing / High ref. flat lightshelf / H=2m, D=0.5m	89.5	0.39	26.1	364
	Base case / High ref. flat lightshelf / H=2m, D=0.5m	88.4	0.36	25.2	358
	Ultra-clear glazing / High ref. curved lightshelf / H=2.5m, D=1.0m	89.4	0.34	25.1	355
	Ultra-clear glazing / High ref. curved lightshelf / H=2.5m, D=0.5m	87.9	0.35	25.2	352
	Silver glazing / High ref. Solid flat lightshelf / H=2.5m, D=1.0m	84.2	0.37	24.9	352
Worst cases	Silver grey glazing / No shading devices	46.5	0.22	29.9	40
	Silver glazing / No shading devices	38.6	0.24	30.9	47
	Light grey glazing / No shading devices	69.9	0.24	30.2	69
	Ultra-clear glazing / Curved glass lightshelf / H=2m, D=1.0m	71.5	0.24	31.2	97
	Ultra-clear glazing / Flat glass lightshelf / H=2.5m, D=0.5m	71.6	0.30	30.3	98

Although replacing the base case glazing with ultra-clear glazing in addition to adding a light shelf was determined to be the best-case scenario, the second best-case scored 358 and does not require a glazing replacement. It could be more economical to use the blue tinted glazing in addition to adding lightshelves. This could be confirmed by adding an economical criterion to the WSM method. If the decision makers value economic criterion over other criteria, in this case a separate equation has to be used in order to assign different weights to each criterion. A feasible equation would be:

$$f(x) = w_j a_{ij} + \cdots + w_n a_{in} \tag{2}$$

Where

$f(x)$	is the sum of criteria scores, such as UDI, MRT, LUR, cost, life cycle analysis ... etc.
w_j	is the weight of each criterion;
a_{ij}	is each criterion score.

Economic analysis is not considered in this study. Future work should follow by investigating the feasibility of the alternative solutions.

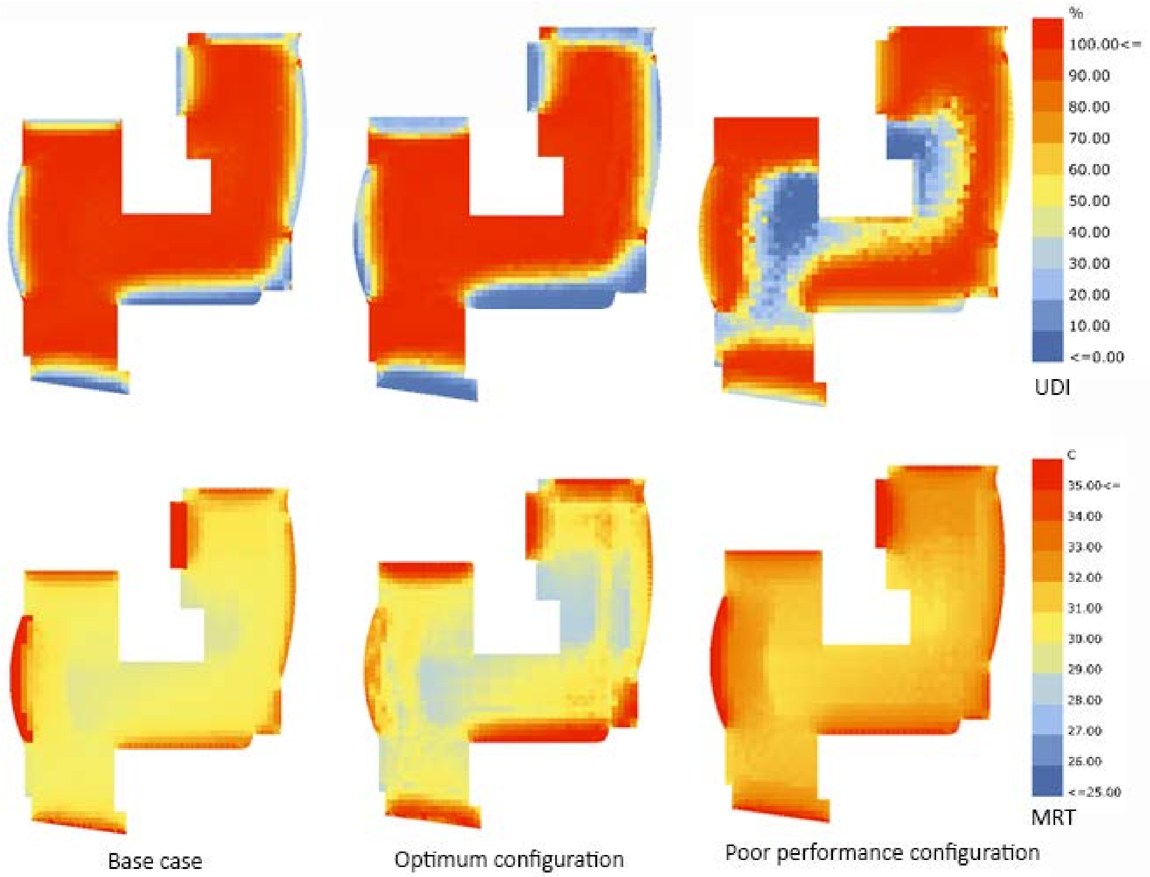

Figure 4 – UDI and MRT maps of the base case, highest performance case and lowest performance case

7 Conclusion

In hot climates, glazed facades are potential sources of undesired solar gain. They can also result in a decreased lighting uniformity and an increased glare, both of which cause discomfort and reduce the daylight performance of employees. Glazed facades can also lead to an increase in cooling loads, which increase the building's energy consumption. This study aimed to introduce a set of alternative configurations that work best in retrofitting facades with large glazing in hot climates to improve daylighting, reduce heat gain and ultimately reduce energy consumption. The study has utilised a parametric approach that facilitated the investigation of 138 different configurations that were later ranked using multiple criteria decision analysis methods. The configurations included different glass types, the addition of lightshelves, and/or the utilisation of perforated double skin facades. It is concluded that a combination of glass with high transmittance and a high reflective light shelf can significantly improve daylighting availability, lighting uniformity, and thermal comfort in the examined office building located in New Cairo.

The results showed that all of the configurations of glazed facades without shading devices are ranked in the bottom ten, although two of them (with the highest VT ratio) achieved high UDI ranks. Among the top 25 configurations, there is only one perforated facade, and the rest are glazed facades with lightshelves. This is mainly achieved due to the positive effect of the lightshelves in enhancing the illumination uniformity distribution that secured a high LUR rank, which in most cases is accompanied by a high UDI or MRT rank. It is noticeable that among the top 25 configurations, only one case has fallen among the top 25 for each of the three criteria. This is the third ranked case, which is an ultra-clear glazing combined with a curved high reflective opaque lightshelf of 1m depth that is placed at a 2.5m distance from the floor.

The best case configuration combined an ultra-clear glazing and flat high reflective opaque lightshelf of a 0.5m depth and is placed at 2.5m from the floor. This increased the base case UDI by more than 5%, it almost doubled the illumination uniformity and it decreased the average MRT by more than 5°C.

The thermo-visual criteria have only been considered in this rank. Therefore, taking more criteria into consideration will lead to different preferences. The economic and environmental criteria are subjects for future study.

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