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Simulating the thermal and daylight performances of a folded porous double façade for an office building in Cairo

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Abstract: The application of Double Skin Facades (DSFs) in hot climates is limited and their potential benefits are still under investigation. Moreover, daylight and thermal performances of the double façade are rarely studied together. In this paper a set of parameters are optimized for the design of a folded porous double façade for an existing office building in Cairo, with an aim of reducing cooling loads while maintaining daylight needs. The design and optimization processes take place using parametric design software, specifically Grasshopper Plugin for Rhino 3D modeller. These software tools were chosen due to the possibility of using evolutionary algorithms for multi-objective optimization, and environmental simulation plugins that provide real-time feedback during the early design phase. The existing building acts as a reference case to which the proposed façade is compared to evaluate its performance in South-East and North-West orientations. It is also compared to a conventional double façade. The paper discusses the effect of the design parameters on the thermal and daylight performances of the façade highlighting their preferred numerical range. Limitations of the software used are addressed, requiring verification of results using CFD simulations in future work.

Keywords: Double facades; hot climates; optimization; environmental performance.

1. Introduction

Façade design plays an important role in the thermal comfort of interior spaces of buildings. Double skin facades (DSFs) in particular are becoming increasingly popular in cold, temperate climates for aesthetic reasons and also for energy efficiency among other advantages (Poirazis, 2006). Most of design guidelines and recommendations of double facades are for temperate climates and aim at the enhancement of buoyancy-driven airflow (Barbosa and Ip, 2014), thus having a big temperature difference between the cavity and external temperature isn't a major problem. A higher cavity temperature enhances the buoyancy effect and natural ventilation. However, having such an increase in cavity temperature will not be favourable in hot areas where specific attention is made to the reduction of cooling loads as much as possible. This is one of the major differences between designing DSFs for hot and cold climates.

Moreover, the daylight performance of DSFs has been rarely addressed alongside its thermal performance in other researches. This is particularly important in hot climatic areas where shading devices or highly reflective glazing (which clearly affect daylight performance) are needed in order to reduce heat gain in the cavity.

2. Aim and methodology

The paper aims at reducing heat gain in the double façade cavity by designing a folded surface that provides self-shading thus reducing direct solar radiation. The folded surface also has perforations distributed throughout the façade area for natural ventilation of the cavity thus increasing heat loss by convection. This is done while taking into consideration its daylighting performance as well.

A recent paper by the authors (El Ahmar and Fioravanti, 2015) addressed the design process behind this proposal and compared its thermal and daylight performances to a room in an existing office building in Cairo (reference case) in the South-East orientation only. Results showed a potential reduction of cooling loads by around 14%, however the daylight performance needed improvement. This paper continues the investigation where modifications are made for improved daylight. To evaluate the thermal and daylight performances of the proposal, they are compared to those of the existing building facade and to a flat DSF to see whether or not they have improved. These comparisons were done in both South-East (SE) and North-West (NW) orientations. The flat double façade is designed based on recommendations concluded from reviewing DSFs in hot climates as will be explained.

This paper represents an exploratory research in which a set of design parameters are optimized using evolutionary multi-objective optimization to achieve a balance between the conflicting thermal and daylight requirements. The optimization process is performed then a solution is chosen for each orientation to compare it with the reference case and flat DSF. The influence of design parameters on both daylight and thermal performances is discussed, and based on them the preferred range of each design parameter is given. The tools used are Grasshopper Plug-in for Rhino 3D modeler v.5 SR8, Octopus plug-in for evolutionary optimization, Archsim plug-in for thermal simulations which runs on EnergyPlus v.8.2 and DIVA v.3 plug-in for daylight simulations which runs on Radiance and Daysim.

3. Literature review

Since most of the research about double façades was in temperate climatic areas as mentioned earlier (Barbosa & Ip 2014; Poirazis 2006), an exploration of examples in hot climates was necessary.

Hamza et al. (2007) compared thermal and daylight performances of a continuous-type DSF (in which there were no obstructions in the cavity) with a corridor-type in which there were perforated walkways (50% open) every two floors. They both had air openings at the top and bottom of the cavity but no shading devices were used. Only the corridor-type had air openings in the outer façade layer at each floor level. Simulations were done on a summer day in the climate of Cairo. They compared thermal and daylight performances of the two cases in East and West orientations. Their results showed that direct solar radiation is the main heat gain source compared to surface radiation and convection heat fluxes in both orientations. The corridor type cavity temperature was 1.5°C lower than the continuous one. This shows the importance of multiple openings for ventilation throughout the height of the façade and not just at the top and bottom.

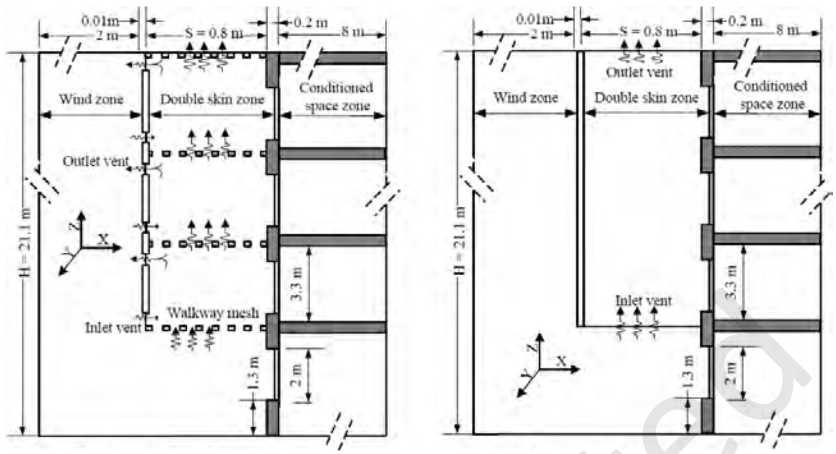


Figure 1: The corridor (left) and continuous (right) double facades compared by Hamza, et al., (2007).

However the corridor type resulted in a darker indoor environment indicating the need of more use of artificial light. In both orientations; they resulted in glare problems near the windows which will require the use of blinds. It represented an interesting example as it showed that despite the potential energy savings due to improved thermal performance, they were associated with increased energy use for artificial lighting. Hamza (2008) conducted another study in Cairo, comparing a single façade that had single-pane clear glazing, and a DSF that had vents at the top and bottom. Cooling loads were compared for the four orientations using different glazing properties for the outer façade layer. Reflective glazing provided the most reduction in cooling loads (32% in all orientations) compared to double clear and double tinted glazing which produced a 7% increase and 11% decrease respectively.

Another study took place in the extreme hot climate of the United Arab Emirates. Radhi et al. (2013) modelled an existing building with a double façade, and compared it with a single façade. The double façade had air openings at each floor level, and at the top and bottom of the cavity. They performed these comparisons in four orientations. They also compared different glazing properties and cavity depths to see their influences on cavity temperature, airflow and cooling loads. The double façade resulted in lower cooling loads in all orientations except in the North where a 3% increase was estimated. Cavity temperatures were generally not much different than the air temperature outside due to the presence of openings along the cavity height. They recommended cavity depths between 0.7m and 1.2m and that the solar heat gain coefficient (SHGC) and U-value of the outer glazing layer are very important. They estimated a 17% reduction in cooling loads due to the presence of the double façade.

Hashemi et al. (2010) also modelled an existing double façade in Tehran and compared the cavity temperatures and cooling loads to that of a single façade in four orientations. The double façade had Aluminum vents which were 1.5m high distributed throughout the façade height. Their results showed that cooling loads in daytime were reduced, however during the night they increased due to the lack of night ventilation in the office rooms. Despite the lack of shading devices, and the use of single glazing in both the outer and inner facades layers, natural ventilation alone was able to improve the overall performance in the climate of Tehran. After reviewing the mentioned examples among others

(Baldinelli, 2009; Papadaki et al. 2014; Barbosa and Ip 2014), the following considerations are seen as the most important for the architectural design of DSFs in hot climates:

- Multiple air openings along the height of the outer facade layer to prevent over heating
- The glazing properties of the DSF (balance between low U-Value and low Solar Heat Gain Coefficient) especially if no shading is used.
- Since solar radiation is the main heat gain source, it is highly recommended to use shading devices.
- Shading elements are preferably placed externally and not in the cavity
- Recommended cavity depth range: 0.7 m to 1.2 m.
- Cavity should be higher than ground level and higher than roof level.

It is important to note that studying the daylight performance along with different façade configurations was only addressed by Hamza et al. (2007). It was the only example found (to the authors' knowledge) that studied both daylighting and thermal performances of double facades in a hot climatic area.

4. Reference case & flat DSF

Figure 2: Reference case: B19 office building in the Smart Village, Cairo. Architect: Engineering Consultants Group (ECG).

The Smart Village in Cairo is a contemporary business district that represents state of the art in office building design in Egypt. One of these buildings was chosen for this study (Figure 2), which has a blue-tinted curtain wall façade having the same material specifications as all other buildings in the Village; non-operable double-pane tinted glazing (with a light transmittance of 0.37and solar transmittance of 0.43) and aluminum cladding. Building drawings, façade material specifications, and readings of monthly cooling energy consumption (for the year 2014) were obtained. Only one office room is addressed in this paper, representing a typical mid-floor space with the dimensions of 5 m in width, 8 m deep, and 4.1 m high. It is studied in SE and NW orientations as in the existing building. Digital simulations of annual cooling loads in SE and NW orientations predicted a consumption of 121 KWh/m^2 and 112 KWh/m^2 respectively, which was in close accordance with actual readings of the building which indicated that average annual consumption is 113 KWh/m^2.

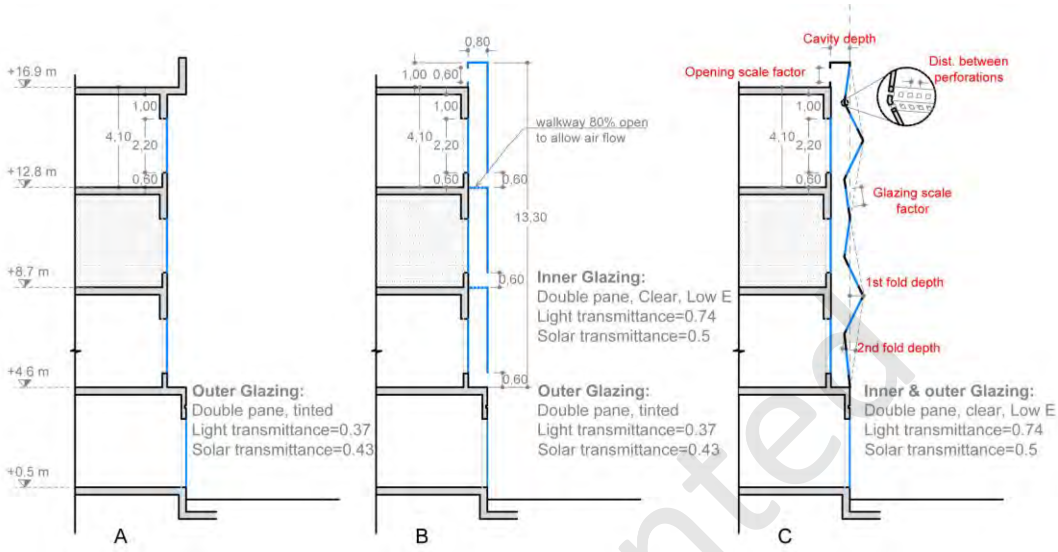


Figure 3: Cross-sections illustrating the geometric and glazing properties of each façade: A) Existing reference case, B) Flat double façade with air openings at each floor level and at top, C) Folded façade showing the parameters used in the optimization process (the 3rd fold depth omitted for simplification).

A flat double façade is proposed that is very similar to that proposed by Hamza et al. (2007) as it was also designed in Cairo. Figure 3(B) describes its geometrical configuration and the glazing materials used. It is a fully glazed double façade, 9 m wide, 13.3 m high with a 0.8 m wide cavity including perforated (80%) walkways and air openings at each floor level. Air openings are present also at the top.

5. Proposed folded porous DSF

Many possible folding patterns can achieve the desired effect of self-shading. For this design proposal the triangular Pinwheel pattern has been chosen (Figure 4). It is seen as aesthetically pleasing and also folded surfaces would be triangular and therefore flat, making it relatively easy to construct compared to other double-curved folded surfaces. It is an iterative fractal pattern that takes an input triangle and divides it in a certain way (1st iteration), then a certain point in the triangle is moved perpendicularly to its plane, creating the folding effect (Figure 4B), this moved distance is called the fold depth. The same division logic is applied again to the resulting triangles and so on (subsequent iterations). When applied to the double façade, the first iteration was extracted to act as the main structural elements that would bear the load of the façade and also contain a network of small 2.5x2.5 cm perforations creating the intended *porous* effect. The overall dimensions are 9x13 m as the flat DSF.

The geometrical design *parameters* that control the DSF configuration (Figure 3C in red) and affect the performance of the façade are; depth of the 1st, 2nd, and 3rd fold iterations, cavity depth, glazing scale factor, distance between the façade perforations (which controls their density), and a scale factor for air openings at the top of the façade. It is important to clarify that the glazing scale factor represents the biggest possible number to be used to scale down the size of each triangular face to create a glazed opening. This list of numbers (scale factors) is set to be inversely proportional to value of insolation on each face. Thus the bigger the insolation the smaller the glazing scale factor and vice versa.

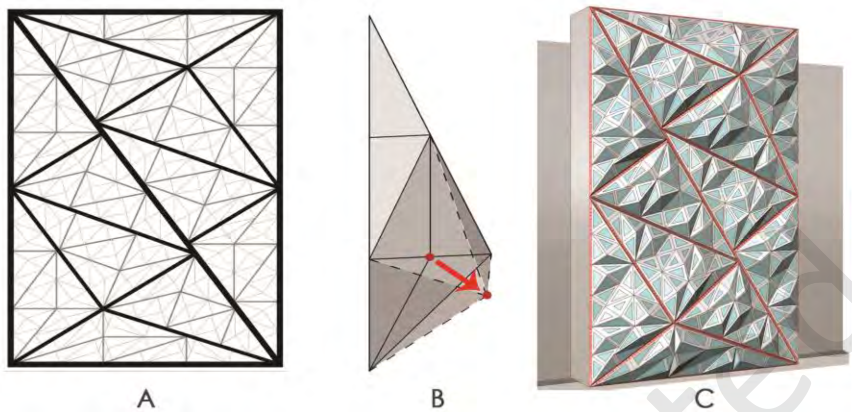


Figure 4: A) Hierarchy of 3 iterations of the triangular pinwheel pattern, in black, grey and light grey respectively. B) Adding a third dimension to the pattern. A point in each subdivided triangle is moved perpendicularly to its plane to have a folding effect. The moved distance is called the fold depth. Each iteration can have a different fold depth that could be positive (outwards) or negative (inwards). C) The pattern applied on part of the building façade where one room is studied. Overall dimensions are 9 m by 13 m. The 1st iteration (in red) includes perforations.

The performance criteria chosen to evaluate the performance of the double façade are the cavity temperature and the percentage of the room area with a Daylight Factor (DF) greater than 2 in the office room. The DF is used only in the evolutionary optimization phase as an indicator of better/worse daylight performances so that the solver would select the best performing solutions in a given generation to proceed to the next. Afterwards a final solution is selected when the optimization process is finished, and the more accurate Daylight Autonomy (DA) metric is used instead of the DF.

All of the design parameters affect the performance criteria in different ways. At first a preliminary testing phase was performed. The design parameters were all given default values and then each one was tested individually to have a basic understanding of its influence, and consequently assign a suitable search range in the optimization process. For example the preliminary testing showed that the presence of the perforations together with openings at the top increase airflow and could decrease the cavity temperature by up to 2°C. Therefore their search ranges were restricted to the values achieving relatively bigger surface area of openings. There are many possible combinations among these parameters and it is very difficult to manually test each combination and to see its effect on the conflicting performance criteria. This encouraged the use of evolutionary algorithms for multi-objective optimization, to help in finding a solution achieving a good balance between the required criteria. The preliminary testing phase helped in setting the search ranges of each parameter, to avoid wasting time in solutions that have low performances.

6. Optimization Process

Using Octopus Plugin for Grasshopper, this process was done once for each of the SE and NW orientations on a typical summer day with an average ambient temperature of 32°C and average wind speed of 4.9 m/s. The results were exported to excel files then viewed in Pollination (Roudsari, et al. 2015) web application for exploring multi-dimensional data. It was particularly useful due to the ability of choosing a certain value or a range of values of any parameter/criterion and see the corresponding other parameters of that solution. For example in Figure 5, results were narrowed down to those having the least cavity temperatures enabling the observation of possible tendencies of the design parameters that led to these results.

6.1 Effect of parameters on cavity temperature

The range of cavity temperature values was very narrow (33.64°C to 33.91°C) and air change rates were generally high (40 ach to 150 ach), this is due to the search range of each variable that has been narrowed down. The glazing scale factor, even in its highest value (0.99) corresponded to a window-to-wall ratio (WWR) of 0.44, so a considerable amount of shading is still applied anyway which reduces cavity temperatures compared to a fully glazed DSF. Fold depths strongly influenced both thermal and daylight performances. The numerical value of each fold depth on its own does not count as much as the differences in directions among them. Bigger air opening areas were always associated with higher air change rates and less temperatures. But when they exceeded around 45 ach, no improvement to the temperature was observed. The parameter ranges that led to lowest temperatures were:

- Folds: tended towards opposite extremes (folds in opposite directions); first and third fold depths had maximum positive values (1 m and 0.4 m), while the second had maximum negative value (-0.5 m).
- Cavity depth: tended towards higher values and ranged between 1.4 m and 1.5 m.
- Glazing area scale factor: tended towards minimum (corresponding to a WWR=0.2), which was an expected result.
- Air openings: tended to have mid-range values (corresponding to a total area of 4.4m^2 for openings at the top and 0.9 m^2 for perforations).

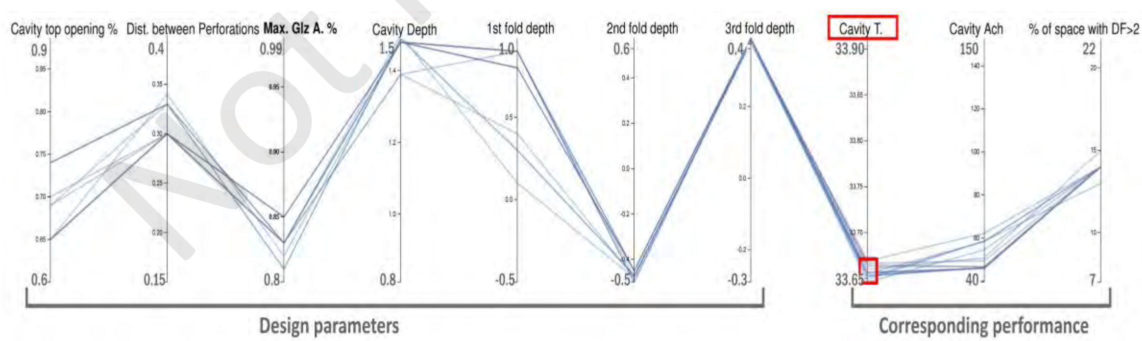


Figure 5: Results of optimization process that achieved the minimum cavity temperature values. Results visualized using Pollination web application (Roudsari, et al., 2015). The upper and lower limits for the design parameters represent their search ranges in the evolutionary solver.

6.2 Effect of parameters on Daylight

Despite the expected effects of glazing area on cavity temperatures and room daylighting, the same glazing area could result in different performances if the rest of the variables are changed. For example a high glazing scale factor of 0.98 (WWR=0.44) can result in 22% or 13% of room area having a DF greater than 2, when different fold configurations were used. The main difference observed was that of the *first* fold depth which was 0.8m and -0.4m respectively. This shows the strong influence of folds on daylight performance, especially the first fold depth as it is the largest in the facade. The highest DF performance reached was 22% of the space, corresponding with a temperature range between 33.6°C and 33.9°C. The design parameters that led to highest daylight performances were:

- Folds: first fold depth clearly tended towards maximum positive values (0.9 to 1.0 m). The second and third fold depths did not show a clear value range but they were either near zero or positive values. In general, they tended not to be folded in opposite directions.
- Cavity depth: ranged between 0.97 m and 1.29 m.
- Glazing area scale factor: tended towards maximum values ranging between 0.97% and 0.99% (corresponding to a WWR=0.42 to 0.44).

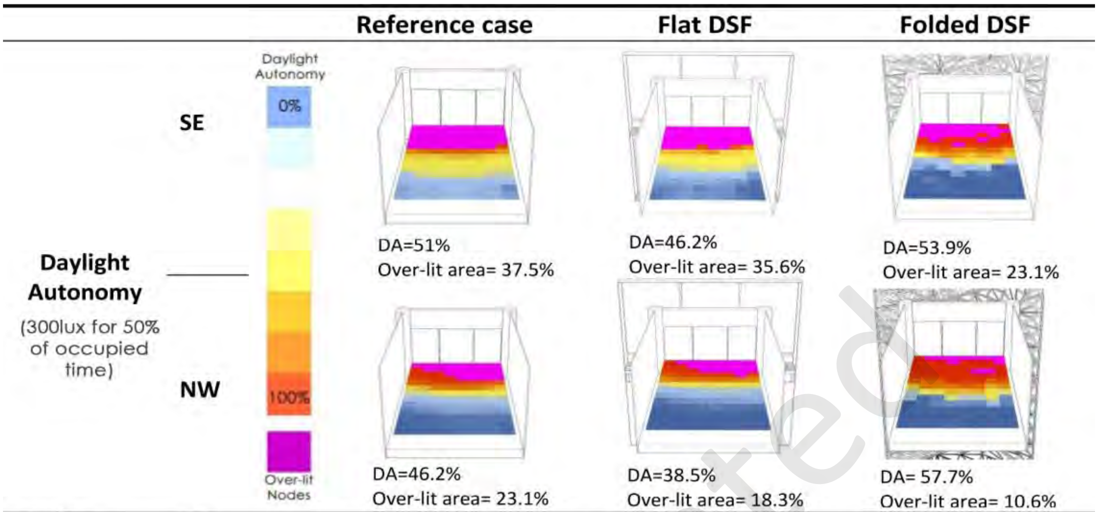
The aforementioned observations were for the SE orientation. Very similar tendencies were observed in the NW; the main differences were that the fold depths did not show the clear tendency towards opposite extremes, cavity temperatures were slightly less and there were more possible solutions achieving good trade-offs between daylight and temperature. In general, for both orientations, many different combinations of parameters produced very similar results. This gives the architect some freedom to choose according to other preferences (aesthetic, structural, etc.).

6.3 Modifications to improve daylight performance

During the optimization process, the glazing of the inner façade was initially left as that used in the reference case. This justifies the poor daylight performance. In practical terms, if one would decide to build a double façade like this, then the choice for glazing specifications of the inner façade layer would not be a tinted one that only transmits 37% of light inside as that used in the reference case. This is because the inner façade layer has already become shaded by the added layer which reduces the amount of light entering the office spaces. Consequently, it has been decided to use a different inner glazing which is double Low-E clear glazing (Figure 3C).

7. Comparison with reference case and flat DSF

A solution was selected for of each orientation. More accurate simulations of daily cooling loads for the whole month of July, and Daylight Autonomy (DA) have been performed as seen in Figure 6. It is important to note that the flat DSF was assigned an outer glazing different from that of the folded one. It transmits less light and solar energy to compensate for the lack of shading devices. The folded one however is in itself a shading device, so it did not need the same glazing properties (as in Figure 3).



		Reference case	Flat DSF	Folded DSF
Cooling Loads (KWh)	SE	900.9	861.8 (4% decrease)	818.0 (9% decrease)
	NW	916.9	897.0 (2% decrease)	807.0 (12% decrease)

Figure 6: Daylight Autonomy and cooling loads for July for each case in SE and NW orientations. Note that the folded DSFs are not the same since a solution was chosen for each orientation.

The reference case in the SE barely achieves the DA benchmark (LEED v.4), which is 50% of the space receiving at least 300 lux for half of the occupied time, and is slightly below it in the NW. In the reference and flat DSF cases a considerable amount of the space is over-lit near the windows, receiving more than 3000 lux for at least half of the occupied time. This requires the use of blinds and thus more energy for artificial lighting. The flat DSF slightly decreased DA, with slight improvement to the glare problem, and decreased cooling loads by only 4% and 2% in the SE and NW respectively. This means that shading devices or higher reflective glazing is required to improve the thermal performance, but it will be at the expense of even less DA.

Figure 7 shows that the cavity temperatures in the folded DSF were always higher than ambient temperatures by only 2°C and around 1.7°C lower than the flat DSF despite changing wind speed and direction. Consequently the folded DSF showed better improvement to cooling loads as they were decreased by 9% and 12% in SE and NW orientations. This decrease was associated with better DA, in fact better performance was observed in both orientations with a considerable reduction in the over-lit area as light was better distributed reaching deeper into the space. The modified glazing properties of the inner façade layer were important to achieve this DA performance; when the inner glazing was left as in the reference case, reduction in cooling loads reached 15% but was associated with a DA of only 45% of the space (El Ahmar and Fioravanti, 2015).

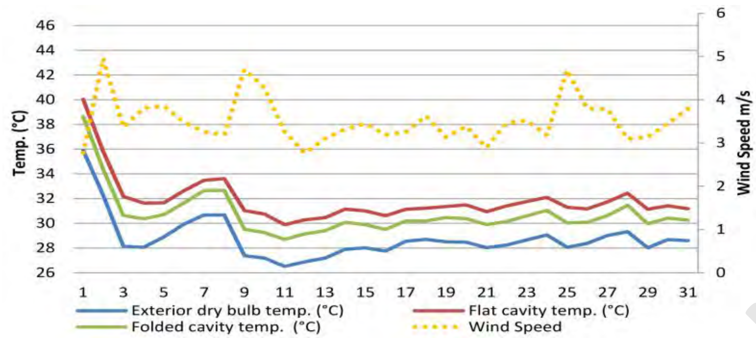


Figure 7: Cavity average temperatures for flat and folded DSFs in SE orientation, in July. The Wind direction is usually NE except for the 1st day and last week of the month when it is S/SE.

7.1 Software limitations

Digitally modelling a double façade cavity is a complicated task since airflow, air temperature, and daylight interact with each other and affect the resulting behaviour (Poirazis, 2006). Based on the level of resolution of the simulations, they can be categorized into *macroscopic*; dealing with whole building systems over periods of time like EnergyPlus and *microscopic* which focuses on smaller spatial and time scales, Computational Fluid Dynamics (CFD) are typically used in this level (Hensen, 2002). Despite the advantages of CFD, it is difficult to use in early design phases as it is too detailed, it needs high computation power and advanced user knowledge. The use of EnergyPlus in simulating double façades is debatable as it uses the Airflow Network model which assumes that each thermal zone has a uniform temperature distribution, and it doesn't consider the cavity airflow pattern (EnergyPlus, 2014). Several studies (Zhang, et al., 2013; Sabooni, et al., 2012; Kim and Park, 2011) recommend coupling EnergyPlus with a CFD tool to complement each other's limitations.

8. Conclusion

The thermal performance of DSFs is still not widely studied in hot climates as those in cold ones, and their resulting daylight performance is rarely addressed. The paper presented an exploratory investigation of the application of an irregular DSF for the improvement of thermal and daylight performances of an office room in Cairo. The proposal was compared to the reference case as well as a flat DSF designed based on observations from previous studies. To attempt to find a trade-off between conflicting daylight and thermal performances of the folded DSF, evolutionary search algorithms were used. The tools proved very useful in finding a suitable combination of the numerous design parameters, to achieve a balance among the performance criteria.

Results showed that the folded morphology which provides self-shading, in addition to air openings and perforations that improve cavity airflow are important in reducing the cavity temperature. Cooling loads were reduced while improving daylight performance. The selection of glazing properties was important to achieve these results. This encourages further explorations into irregular DSF configurations for higher reduction in cooling loads. Future work also includes the verification of the results simulated by EnergyPlus using CFD. It is expected that there will be inaccuracies in EnergyPlus results. However the purpose is to know the degree of inaccuracy and whether EnergyPlus can be relied on in differentiating between best and worst-performing solutions. This is quite important since the use of CFD is still not practical in early design phases. In all cases the physical phenomena occurring within the cavity of a DSF are complex to accurately simulate using computers, even with CFD, especially with complex geometrical façade configurations.

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