OPTIMIZATION OF OFFICE BUILDING FAÇADE TO ENHANCE DAYLIGHTING, THERMAL COMFORT AND ENERGY USE INTENSITY

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ABSTRACT

The aim of this paper is to examine a framework in which an office building façade was optimized for the integrated performance of total energy consumption, daylight quality and thermal comfort. A south facing façade of an office space was modelled parametrically for two case studies in Cairo and Munich. The effect of changing the window dimensions, glazing system, insulation thickness, as well as different shading and daylighting systems was analysed using Radiance and EnergyPlus simulation tools. A multi-objective optimization was performed to reach an optimal range of solutions. The results from each case study and the relations between the design variables and objectives for each case were studied. Moreover, the practicality of using a simulation-based multi-objective optimization in generating high-performance design alternatives was examined. The results show that the use of multi-objective optimization for complicated design problems can aid in reaching performative solution and clarify the relations between the design variables and objectives.

INTRODUCTION

Building facades have great impact on the whole building performance. It must fulfil a number of vital functions while maintaining the energy consumption of the building as low as possible. A good façade design should help in saving energy while protecting the building occupants from external climate conditions and provide them with comfort. Due to the numerous variables that affect the overall building performance and the multi-objective characteristic of the building performance, architects and designers usually use a trade-off approach to design building facades with better performance.

Passive design strategies are typically used to enhance the performance of facades. Some of the most used strategies include reducing the glazing area, using high performance glazing system, and the use of daylight and shading systems. Reducing the Window-to-Wall Ratio (WWR) is one of the main principles of low-energy buildings design. Most guidelines and standards aim at limiting the glazing area to WWR≤30% but mainly focuses on the energy savings from the HVAC systems without considering the trade-off between lighting loads and HVAC (Lee et al., 2009). Minimizing glazing area can have a negative impact on daylighting availability and distribution, hence increasing the energy load and resulting in poorly daylit working spaces. Moreover, the presence of shading devices can change the optimum WWR (Mangkuto et al. 2016).

Shading and daylighting systems play a significant role specially in side-lit office spaces. The effect of using shading devices with different WWRs on both daylighting and energy use was investigated by several previous studies. A recent review by Krimitat et al. (2016) shows a noticeable increase in number of research papers that examine the performance of shading devices. In a recent research paper by Reinhart et al. (2013) it was found that larger but well shaded glazing areas can provide an overall better performance as it provides better daylighting with insignificant effects on energy use. Optimum WWR also depends on glazing type. Using high-performance glazing systems of several panels and low-e coatings can aid in maintaining reasonable window sizes and good daylighting without compromising energy savings. Hee et al. (2015) reviewed research work on a large number of glazing systems. It concluded that achieving the balance between daylighting and energy remains a crucial and complicated measure that depends on several factors of which the climate background was found to be the most important.

Another vital strategy is the reduction of heat transfer from the building envelope by using suitable wall insulation. According to a recent review by Papadopoulos (2005) thermal insulation remains the most cost effective approach in reducing energy consumption in both new constructions and retrofitted buildings. The thickness of insulation needed and overall wall U-value differs according to geographic locations and climate. Local codes and guidelines usually define the minimum insulation needed to insure a suitable performance of the building envelope. Standards and guidelines for passive strategies are most helpful when dealing with limited objectives and variables. However, when dealing with several variables and objectives it becomes more complicated specially when some of these objectives are conflicting. In such cases, the use of simulation-based optimization methods was found to be an effective approach. Multi-objective optimizations in particular is found to be promising due to the complex and multi-objective nature of design problems. In contrary to single objective optimization, multi-objective optimization doesn't result in a single optimum solution but rather a whole set of possible solutions of equivalent quality (Abraham et. al., 2005). Therefore, decisions could be taken by considering the trade-offs between conflicting objects. Some of the early work on using GA optimization in buildings design was presented by Caldas & Nordford (2002). Several recent research works used this technique in architecture, engineering and construction (Wright, et al. 2013; Asl. et al. 2014; Ashour, & Kolarevic, 2015). Recent publications investigated the trends of the use of optimization tools in research related to building performance. Evins (2013), presented a review for most of the significant work that utilized optimization tools in sustainable building design. The review showed a major increase in the use of optimization tools. It also highlighted the opportunity for future development as nearly half of the research work focused on single objective problems that can be extended by adding more objectives. In another review by Attia et al. (2013), recent publications were classified according to the objectives and design variables. In both reviews some limitations were drawn including the computation time, ease of use, and uncertainty. This paper aims to investigate the practicality of using multi-objective optimization in providing high-performance façade designs. That is made by examining a framework in which building façade is optimized for the integrated performance of total energy consumption, daylight quality and thermal comfort. The optimization variables are the glazing area, glazing system, insulation thickness, and a variety of shading and daylighting systems with different variables.

METHODOLOGY

Parametric model

A parametric model of a south facing single office space was created using Grasshopper plugin for the Rhino 3D CAD software. The office room was assumed to have the dimensions of 4.00m x 6.50m x 3.00m for the width, depth and height respectively.

Daylighting performance, energy use and thermal comfort were analysed. Simulations were performed for two cities: Cairo, Egypt (30°3′N 31°14′E) with hot arid climate and Munich, Germany (48°8'N 11°34'E) that has a temperate humid climate according to Köppen-Geiger climate classification (Kottek et al. 2006). Different settings for the glazing area, glazing system, shading, daylighting system and insulation system were modelled parametrically. The glazing area is divided into upper and lower parts, where the upper part acted as a clearstory window. Both window parts were introduced to the shading devices separately. Seven WWRs were studied together with four glazing systems, four shading systems for each of the windows, and four light-shelf settings. Additionally, the building insulation was increased gradually with 2.5 cm steps until it reaches a total of 25 cm. Overall nearly 20,000 design alternatives could be generated. The details of the parameters are described in the following table (Figure 1, Table 1).

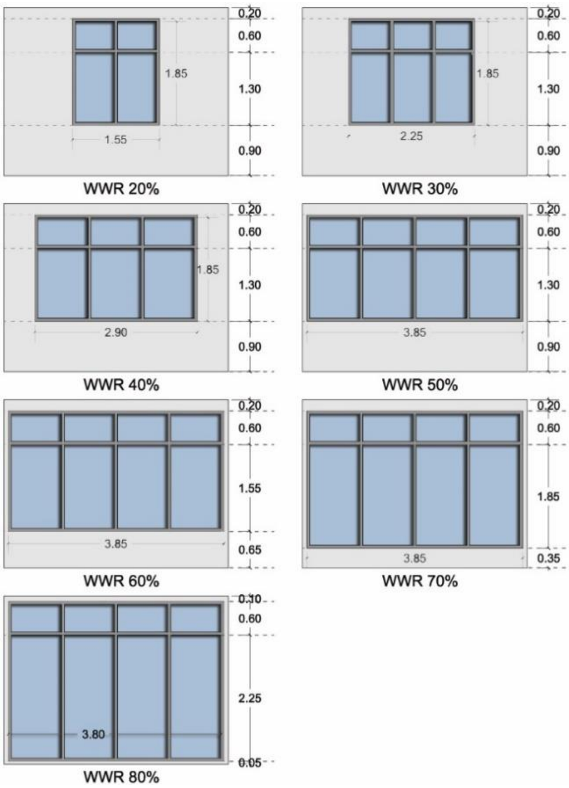

Figure 1 Different WWRs investigated

Table 1 Design variables

Design Variable	**Type**	**Possible Values**	**No. of options**
WWR	Continues	From 10% to 80% (10% step)	7
Insulation Thickness	Continues	From 0.0 to 25.0 cm (2.5 cm step)	11
Glazing system	Discrete	- Single glazing - Double Glazing - Double Glazing with low-e coating - Triple glazing	4
Shading systems (for each window)	Discrete	- No shading - Horizontal shades - Vertical shades - Solar screen	16 (4x4)
Daylight systems (light-shelves)	Discrete	- No light-shelf - External - Internal - External and internal	4
Total number of design alternatives			19,712

Table 2 Radiance simulation parameters

Ambient bounces	Ambient divisions	Ambient sampling	Ambient accuracy	Ambient resolution
sDA /ASE 6 / 0	1000	20	0.1	300

Base case

The research approach in this paper was based on a cross comparison of simulation results. A base case was defined in order to make it easier to evaluate and judge these results. It was assumed to have an un-insulated external wall, WWR of 20%, with double glazing, and without any shadings or light-shelves.

Daylighting simulation methodology

The effect of changing the variables on daylighting performance was measured using DIVA-for-Rhino (V 3.0), a Rhino 3D plugin that is used to interface Radiance and Daysim for annual simulation and illuminance computation (Jakubiec, & Reinhart, 2011). Daylight performance was evaluated using the IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) criteria which corresponds to the latest progress in daylighting simulation metrics introduced in the Illuminating Engineering Society standard IES LM- 83-12 (IESNA, 2012). $sDA_{300Lux/50\%}$ was used to evaluate the presence of sufficient daylight by calculating the percentage of the floor area that receives 300 lux or more for at least 50% of the annual occupied hours. Solutions that achieve sDA ≥ 50% are accepted while sDA≥75% is preferred. The annual sunlight exposure was used to describe the percentage of floor area that receives too much direct sunlight and is used as an indication for visual discomfort (glare) and excessive heat gain. ASE represents the percentage of the floor area that receives more than 1000 lux for at least 250 occupied hours per year. Occupancy hours were assumed to be daily from 8AM to 6PM with hour-saving time. The calculations were made for a reference plane of 60 measuring points in a grid of 0.6m* 0.6m, at a working-plane of 0.85 m height. Simulation parameters are shown in Table 2, and the optical properties of the materials used are presented in Table 3.

Energy simulation methodology

For energy simulations, the Ladybug+Honeybee plugin (Roudsari, M. S. & Pak, M., 2013) was used to interface the EnergyPlus simulation program (US-DOE 2015). The energy use for each design alternative was calculated hourly throughout the whole year for cooling, heating, lighting and equipment loads. The annual energy use per floor area (EUI) was used to compare the efficiency of each design. All surfaces of the tested office space were assumed adiabatic, except the external wall with the glazing. The detailed thermal properties are described in Table 3. Equipment loads were assumed to be 8 W/m² and the lighting power density 11.8 W/m². Lighting load schedules were obtained from the daylighting simulation and the occupancy and equipment load schedules were identical to those used in daylighting simulation. During occupied hours it is assumed that 4 people are present. The space was considered to be fully air conditioned and the HVAC cooling and heating set points were set at 24°C and 20°C respectively.

Thermal comfort

Thermal comfort was evaluated using the Predicted Mean Value model (PMV). The PMV comfort calculator from the Ladybug+Honeybee plugin was used to calculate the Percentage of People Dissatisfied (PPD) for each hour. Operative temperature, mean radiant temperature and relative humidity were obtained from the energy simulation, while both metabolic rate and clothing level were set to 1 *mat* and 1 *clo* respectively. Since the HVAC set point, metabolic rate and clothing level are set to constant values, changes in thermal comfort is due to change in the mean radiant heat derived by the change in the façade construction, glazing type and area. Percentage of Discomfort Hours (PDH) which is the percentage of hours that had PPD more than 10% was aimed to be minimized.

Table 3 optical and thermal properties for building materials

Building element	Properties	
Glazing	Single glazing	τ_{vis}= 0.88; SHGC= 0.82; U-Value= 5.82 W/m²K
	Double glazing clear	τ_{vis}= 0.80; SHGC= 0.72; U-Value= 2.71 W/m²K
	Double glazing low-e coating	τ_{vis}= 0.65; SHGC= 0.28; U-Value= 1.63 W/m²K
	Triple glazing Krypton filled	τ_{vis}= 0.47; SHGC= 0.23; U-Value= 0.57 W/m²K
External wall	Medium colored with 35% reflectance;	
	20cm Concrete block + 2cm cement plaster each side (U-value = 3.1 W/m²K);	
	Thermal insulation thickness (0 to 25 cm); Insulated walls U-Values: 0.91 to 0.114 W/m²K	
Internal walls	Medium colored with 50% reflectance; adiabatic	
Ceiling	White colored with 80% reflectance; adiabatic	
Floor	Carpet floor with 20% reflectance; adiabatic	
External ground	Dark colored with 20% reflectance	
Furniture	Medium colored with 50% reflectance	
Horizontal shadings	Medium colored with 50% reflectance; vertical shading angle = 45°	
Vertical shadings	Medium colored with 50% reflectance; horizontal shading angle = 45°	
Solar screen	Medium colored with 50% reflectance; perforation ratio: 80%; openings proportion: 2:1 (H:V)	
Light-shelf	High-reflective surface with 90% reflectance	

The multi-objective optimization workflow

The multi-objective optimization was performed using the Grasshopper's plug-in Octopus (Vierlinger, & Hofmann, 2013). It is based on the evolutionary algorithm SPEA-2 developed at ETH Zurich (Zitzler, et al. 2001) and applies evolutionary principles to provide Pareto-optimal solutions. A solution is considered a Pareto-optimal if no other solution exists that "would decrease some criterion without causing a simultaneous increase in at least one other criterion (assuming minimization)" (Coello et al. 2006). In other words, Pareto-optimal solutions are non-dominant solutions that are considered as equal solutions. A trade-off between the objectives is therefore essential to judge them. Annual Sunlight Exposure was used as a Boolean objective, so that only cases that achieved ASE less than 10% were considered in the optimization. The optimization was performed for the previously mentioned variables and three objective functions were used: the sDA, EUI and PDH. For each of the two studied locations, the optimization process continued for 10 generations with a population size of 30. Mutation rate was set as 0.5, mutation probability as 0.1 and crossover as 0.8. The optimization workflow is shown in Figure (2). Results were then exported and analysed using Excel and parallel coordinates graphs created by a web-based application "Pollination" (Pollination, 2015).

RESULTS

Simulation and optimization results for Cairo

The base case was found to have an acceptable daylight autonomy with sDA= 65%, however, the overall daylighting performance was considered unacceptable due to the high penetration of sunlight (ASE = 28%). It had a high energy use of 193 kWh/m^2/yr, and a very poor thermal comfort performance (PDH 70%). The main reason behind such poor results was primarily the lack of proper wall insulation and shading. During the optimization 133 unique designs were analysed. Daylight autonomy ranged from 7% to 100%, the lowest energy use intensity was 133 kWh/m^2/yr while thermal comfort ranged between PDH = 2% and 75%. The effect of the design variables on each optimization objective is discussed in the following sections and presented in Figure (3).

Daylighting

Forty-three cases achieved the daylighting threshold and nearly quarter of the cases had better performance than the base case. Cases with preferred daylighting performance tended to have a 50% to 80% WWR, with single, double glazing or low-e coated double glazing. Shadings and light shelves were present in almost every case with few exceptions where it was not needed for the upper window. Three cases achieved the maximum sDA of 100% which is a considerable enhancement given that these cases also had ASE less than 10% and a slightly higher energy use than the base case.

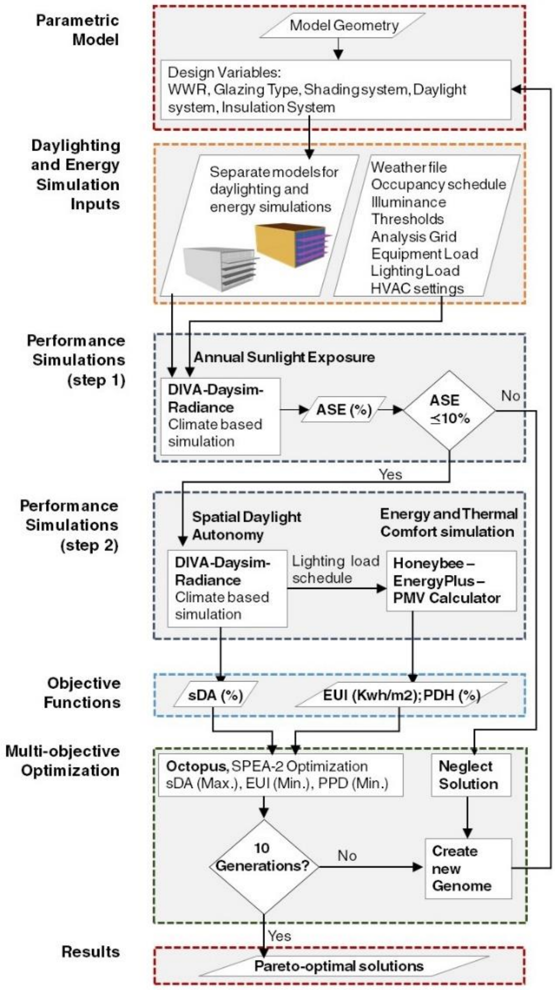

Figure 2 Optimization process diagram

Energy use

Energy savings reached more than 30%. Thermal insulation presented in all cases with an average of 12.5 cm thickness. It played an evident role in reducing the energy consumption and cases with the lowest EUI (133 and 136 kWh/m^2/yr) had maximum insulation thickness (25 cm). Nevertheless, several cases achieved low EUI with lower insulation thicknesses. The combined effect of high performance glazing with shading and light shelves facilitated the increase of the WWR without compromising the energy use, and cases with lowest energy use tended to have larger windows (60-80%). That is mainly because shaded glazing with low U-value helped in maintaining the cooling loads at almost a constant level while large glazing area provided significant savings in lighting loads.

Thermal comfort

Thermal comfort was enhanced steadily throughout the optimization where PDH reached a minimum of 2%. The most effective measure on thermal comfort was the WWR, and most efficient cases had the smallest possible windows (20% WWR), however it didn't achieve sufficient daylighting. The lowest PDH with sufficient daylighting performance was found to be 14% with 30% WWR.

Pareto-optimal

Thirty-six Pareto-optimal solutions were found, from which eleven cases achieved a satisfactory sDA of 50% or more. The majority of the optimal solutions had WWR between 60-80%, double low-e glazing and shadings on both parts of the window. Thermal insulation was also present in all optimal cases with thickness of 12.5 cm or larger. The acceptable optimal solutions are presented in Table (4).

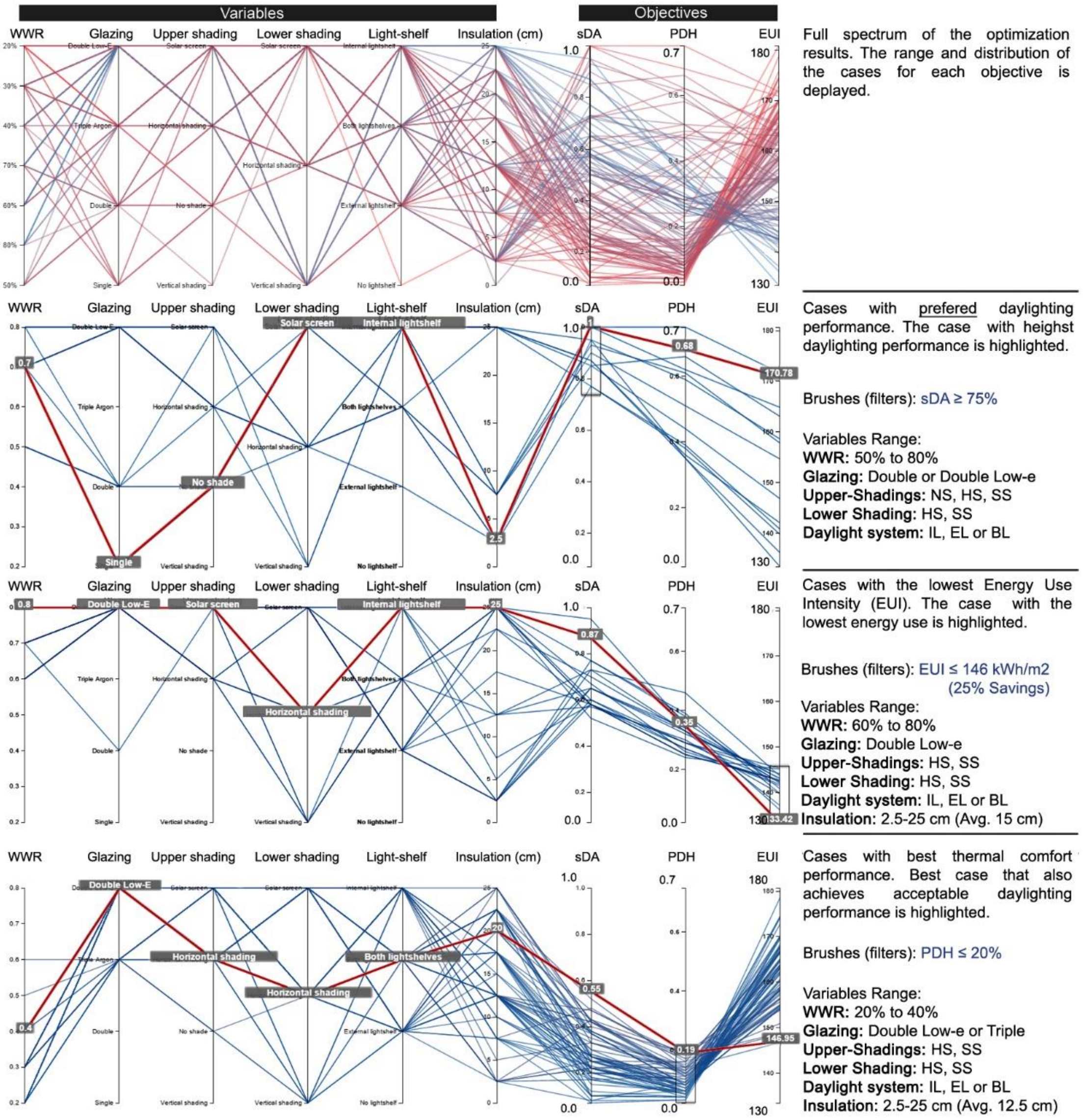

Figure 3 Parallel coordinates plots for the simulated and most performative cases for each objective in Cairo.

Table 4 Design variables and objectives values for Pareto-optimal solutions in Cairo.

WWR	Glazing	Upper-Shading	Lower- Shading	Light-shelf	Insulation (cm)	sDA (%)	PDH (%)	EUI (kWh/m2/yr)
0.70	Single	No shade	Solar screen	Both	2.5	100%	62%	164.88
0.80	Double Low-E	Horizontal	Horizontal	Internal	25	95%	35%	136.18
0.80	Double Low-E	Solar screen	Horizontal	Internal	25	87%	35%	133.42
0.80	Double Low-E	Horizontal	Solar screen	External	12.5	73%	33%	137.14
0.70	Double Low-E	Horizontal	Vertical	Both	22.5	70%	33%	143.17
0.60	Double Low-E	Horizontal	Vertical	Both	25	67%	26%	142.54
0.60	Double Low-E	Solar screen	Horizontal	Internal	12.5	65%	33%	142.39
0.60	Double Low-E	Horizontal	Solar screen	External	25	60%	27%	141.48
0.60	Double Low-E	Solar screen	Solar screen	External	22.5	58%	25%	142.63
0.80	Double Low-E	Solar screen	Solar screen	Both	12.5	57%	30%	139.69
0.40	Double Low-E	Solar screen	Vertical	Internal	12.5	57%	21%	148.11

Simulation and optimization results for Munich

The base case achieved accepted sDA of 55%, however the ASE reached 23%. This resulted in an EUI of 133.85 kWh/m^2/yr and Thermal comfort of PDH= 62%. During the optimization process 145 unique cases were generated. Daylight autonomy ranged from 7% to 85%. The lowest energy use intensity was 91 kWh/m^2/yr. Thermal comfort ranged from 27% to 69%. (Figure 4)

Daylighting

Only one case achieved a preferred performance were the sDA reached 85%. Several design alternatives with most WWR and glazing types achieved acceptable sDA, with the exception of cases with WWR equal to 20% and 40%. For the upper window solar screen, horizontal shading and even unshaded glazing was found to be useful. On the other hand, cases with unshaded lower window, vertical shading or without light-shelves had a high penetration of direct sunlight that resulted in a high ASE and therefore were excluded during the optimization. Light-shelves in particular were found to be effective, as all successful cases had light-shelves.

Energy use

The energy use was reduced drastically throughout the optimization from 133 to only 91 kWh/m^2/yr, with nearly 30% reduction. The effect of wall insulation and high efficient glazing are the main reason behind this reduction. It is worth noting that the cases with the least energy use had also much lower WWR, which affected the daylight performance. Nonetheless, a Pareto-optimal case achieved sufficient daylighting with only 92.3 kWh/m^2/yr. Once more horizontal shading and solar screens were found effective.

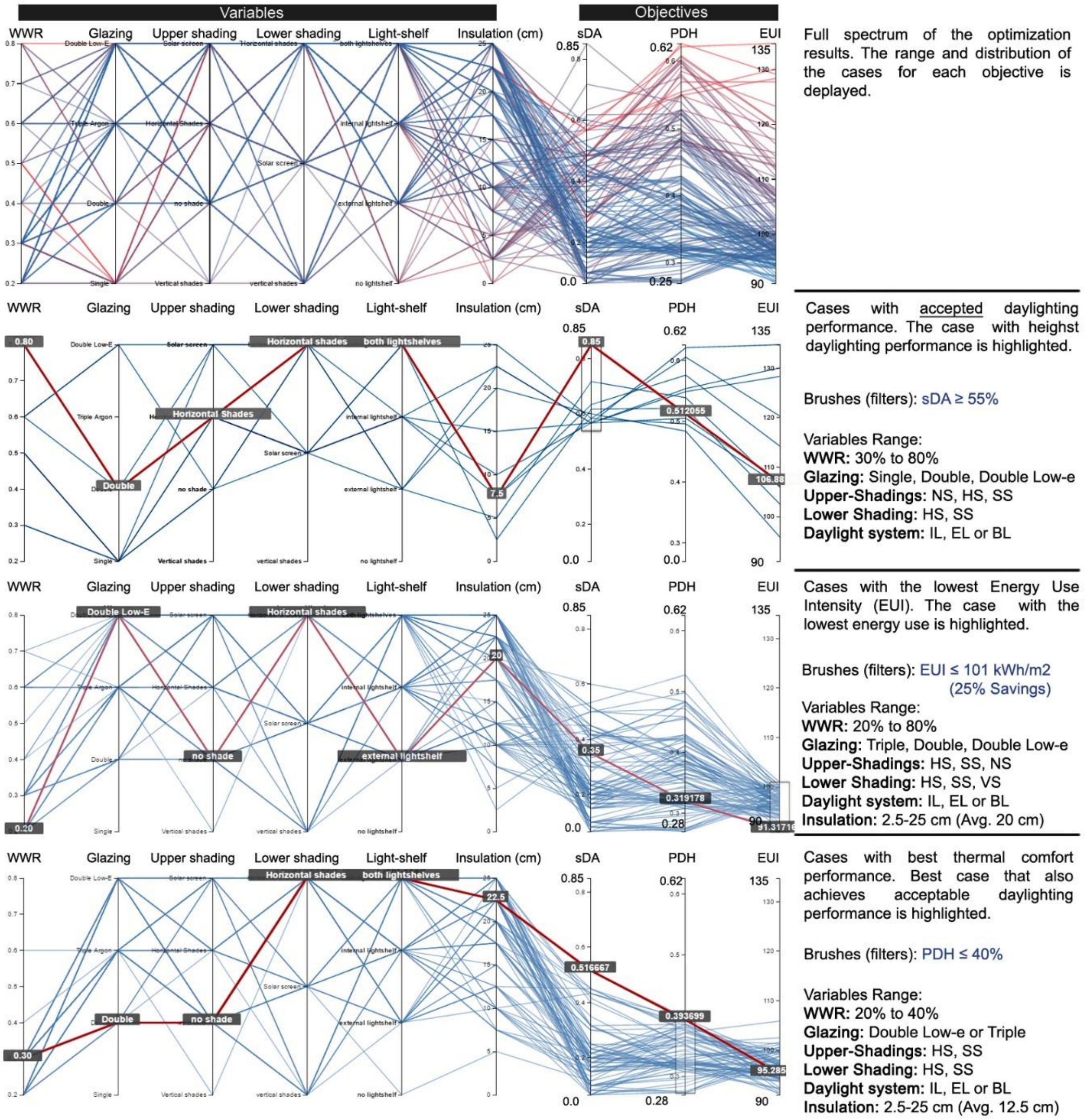

Figure 4 Parallel coordinates plots for the simulated and most performative cases for each objective in Munich

Table 5 Design variables and objectives values for Pareto-optimal solutions in Munich.

WWR	Glazing	Upper-Shading	Lower- Shading	Light-shelf	Insulation (cm)	sDA (%)	PDH (%)	EUI (kWh/m2/yr)
0.60	Triple Argon	No shade	Horizontal	Both	22.5	52%	40%	92.33
0.30	Double	No shade	Horizontal	Both	22.5	52%	39%	95.29
0.60	Double Low-E	Solar screen	Horizontal	External	20	60%	48%	95.77
0.60	Double Low-E	No shade	Solar screen	Both	2.5	62%	52%	102.44
0.80	Double	Horizontal	Horizontal	Both	7.5	85%	51%	106.88
0.30	Single	No shade	Horizontal	Internal	15	57%	51%	107.09

Thermal comfort

Thermal comfort was enhanced gradually, yet enhancements were mainly connected to the reduction in the WWR. That resulted in an inverse proportion relation between daylighting and thermal comfort. As a result, despite the PDH reached a minimum of 27%, cases that achieved acceptable daylighting had a minimum of 40% PDH. Further enhancements for the HVAC system might be needed in this case.

Pareto-optimal

Thirty-one Pareto-optimal solutions were produced from the optimization. However, only six cases achieved an acceptable sDA with variety of design variables. Table (5).

DISCUSSION AND CONCLUSION

This paper investigated the use of a multi-objective optimization framework to arrive at high-performance façade designs. A parametrically modelled office facade was optimized for the climate conditions of Cairo and Munich. The objectives of the optimization were enhancing the daylighting performance, energy use and thermal comfort. Several passive strategies were used as the optimization variables.

The results showed the capability of the process to provide diverse design alternatives with enhanced performance in both case studies. Reduction in energy use reached more than 30% in both cases, while the daylighting performance reached adequate levels with a maximum sDA of 100% and 85% in Cairo and Munich respectively. Thermal comfort was also improved considerably compared to the base case, but remained within unsatisfying level in most cases. Since the cases were assumed to be fully air conditioned, the HVAC system might also need to be optimized for further enhancement in thermal comfort.

General trends were found to emerge from the results which also coincide with previous research. The effect of wall insulation was obvious in both cases and played an essential role in reducing the energy use. Similarly, high performance glazing and in particular the double glazing with low-e coating was present in most of the successful cases. The use of shading devices was more effective in the case of Cairo and facilitated the use of windows with considerably higher window-to-wall ratios. This can be explained in the light of the excessive presence of sunlight in Cairo where the shading devices and high glazing succeeded in blocking the direct sunlight and reducing solar gain and therefore keeping the cooling loads at almost constant level. Concurrently the large glazing area benefited from the available diffused lighting in reducing the lighting load and hence the overall energy consumption. On the other hand, in the case of Munich, lower window-to-wall ratios had better energy performance, as savings from the use shadings and high-performance glazing could not match the increase in heating load due to the high window-to-wall ratios. Light-shelves were found to be always useful and were hardly absent in all successful solutions in both cases.

In conclusion, it became apparent that the use of multi-objective optimization for complicated design problems can aid at reaching performative solution and clarify the relation between the design variables and objectives. The effect of the different variables on each objective can be separately and thoroughly analysed, while trade-offs and overall performance can also be investigated. The main downside of the optimization process lies in the duration of computation time. The optimization process for each of the two case studies consumed nearly 48 hours on a desktop computer with 1.6 GHz i7 processor and 6 GBs of RAM. The coupling of the optimization tool with different simulation engines and software limited the use of parallel implementation and didn't utilize the full computing power. This can be a serious obstacle specially when considering more complex design problems and much larger number of design solutions. Using surrogate models or parallel implementation can enhance the framework. The continuous improvements in both optimization and simulation tools, potential for further research is apparent in the diversity of design problems that could be defined and the endless number of variables and objectives that could investigated.

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