

An optimization of thermal, visual and energy indicators for retrofit with photobioreactors in the mediterranean climate

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Abstract. There is a need for innovative products that cause fewer carbon emissions in the construction industry. Photobioreactor (PBR) façade elements can produce microalgae for biomass, food, or raw materials for various industries. The harvested algae also catch carbon during growth. Its use as a façade element affects the thermal and visual comfort of occupants and the energy consumption of the integrated building. However, very few built examples and physical model development are in progress. This paper deals with integrating PBR to retrofit the south façade for an office building in the Mediterranean climate. It uses multi-criteria optimization simulations to increase occupants' thermal comfort while decreasing total energy consumption and increasing visual comfort. Pareto-optimal results show the effects of various design variables, including PBR properties, heating and cooling setpoints, wall and insulation material and thickness, and window-to-wall ratio (WWR). The results show that alternative retrofit options are better than the existing building for all optimization targets. The heating and cooling setpoints are the most effective design parameters in determining energy consumption, while PBR properties affected the thermal and visual comfort the most. In conclusion, more research is necessary to realize PBR retrofits now, but preliminary results show promise.

1 Introduction

Decarbonization and net-zero greenhouse gas emissions are on the agenda of the United Nations, the European Union, and many other organizations [1]. Existing buildings are a significant source of emissions, with around 28% of global CO₂ emissions occurring from building operations [2]. Therefore, retrofitting buildings is an opportunity to reduce operational energy emissions and increase its contribution to reducing the carbon footprint on the built environment [3]. Hence, providing cost-effective, innovative products or solution packages for the building envelope is necessary. Here, microalgae, which are the source of approximately 50% of the world's oxygen production today [4], can become a solution. Throughout their lives, microalgae take nutrients and CO₂ and turn them into oxygen and various valuable products. The research on using photobioreactors (PBRs) in building façades to grow microalgae is growing. The first full-scale façade application of PBR façades is the BIQ building. Yearly experimental results show 30 kWh/m² of biomass and 150 kWh/m² of thermal energy were produced from the 200 m² PBR facade application, and 6 tons of CO₂ equivalent carbon emission reduction from [5]. Another façade application is the "city curtain" exhibited in Dublin for the 2018 Climate Innovation Summit. The "curtain" placement is on top of the existing façade of

the Dublin Printing Works office building, where it captures approximately one kilo of CO₂ per day from the atmosphere, equivalent to the daily amount of CO₂ captured by an estimated 20 large trees. Moreover, the bioluminescent microalgae give a light sheen in the dark [6]. Warren et al. [7] designed a microalgae facade system. The façade system effectively reduced the amount of carbon dioxide in the interior (200 ppm CO₂ reduction) and thus improved indoor air quality. Besides these projects, some small-scale prototypes exist. Talaei and Prieto [8] provide a review of PBR integration in buildings. Todisco et al. [9] validated a thermal model for the PBR in Modelica simulation software. Negev et al. [10] proposed another method to look at design variables for a PBR façade. Lo Verso et al. [11] used [10]'s values to design a PBR shading system for a library. Talaei et al. [12] also used [10]'s values to parametrically look at some design parameters effective for cold, semi-arid climates. This paper researches to answer the question: "Which design parameters affect the energy consumption, thermal comfort, and visual comfort the most for a PBR façade integration?". The proposed optimization method helps establish a balanced relationship between objective functions [13] and makes climate-adaptive renewal possible. To the best of the authors' knowledge, there was no previous published study of a PBR-integrated building that studied thermal comfort beside the authors' previous works [14] and [15], which looked at the effect of

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different climates in Turkey for other façade configurations.

2 Materials and methods

This research relies on building energy simulation, so validating the simulation is the first step. The examined building (in Figure 1) is in Izmir, Turkey (38° 22' N 27° 11' E), and its climate is Csa according to the Köppen-Geiger weather classification. It is an office building with a basement, ground floor and four standard floors. It was modelled with Rhinoceros-Grasshopper, and the energy simulation engine used is Energyplus/OpenStudio. The visible transmittance (VT) of the existing building's window is 0.236. Building activity data and materials are detailed in Çıldır et al. [16] and Yaman [17] and used as input in the simulation. The indoor temperature results obtained from simulation were compared with actual temperature measurements and validated according to the ASHRAE Guideline 14 [18]. According to this guide, the validation criteria are Normalized Mean Deviation Error (NMBE) and Coefficient of Variation of Root Mean Square Error (CV (RMSE)), and the values we obtained are 9.08% and 12.72%, respectively, and meet the desired threshold.

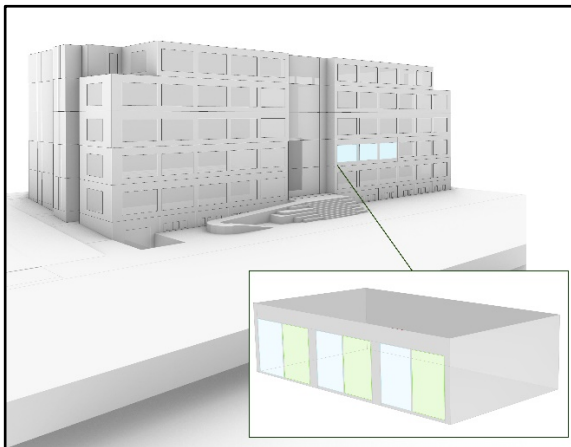


Fig. 1. The proposed PBR façade.

The second step rearranges the building geometry according to the retrofit façade proposals. The office dimensions are 14.70 x 8 x 3.85 m, and the WWR is 80% for the existing façade. There are three PBRs and three windows in the alternative design. PBRs are flat plates with a growth medium depth of 0.06 m. Then PBR element is defined for simulation. For calculations of visible transmittance (VT) and solar heat gain coefficient (SHGC) as proposed by Negev et al. [10], VT of microalgae specie *Chlorella vulgaris* growth are measured by a spectrophotometer. The measurements were for *C. vulgaris* grown for ten days. At the end of the growth process, the VT of the microalgae between 300-950 nm was measured and defined as 100%. Then, the VT values of concentrations between 10% and 100% were determined. The U-value calculated based on ASHRAE [19]. Since minimal changes were detected in the U value throughout the year, a single value (2.14 W/m²K) was entered. The calculated VT and SHGC values are in Table 1.

Table 1. Properties of windows with different microalgal concentrations.

Properties of window	10%	20%	30%	40%	50%
VT	0.52	0.32	0.16	0.13	0.09
SHGC	0.60	0.44	0.30	0.28	0.25
U value	2.14W/m ² K				
Properties of window	60%	70%	80%	90%	100%
VT	0.06	0.05	0.04	0.03	0.02
SHGC	0.22	0.22	0.21	0.21	0.19
U value	2.14W/m ² K				

Afterwards, daylight and energy simulations are run to calculate useful daylight illuminance (UDI) for visual comfort, energy use intensity (EUI) for energy consumption, and thermal comfort violation (TCV) for thermal comfort. Daylight simulation was carried out with Radiance/Daysim simulation engines. Reflection values of the ceiling, floor, interior and exterior wall are 0.8, 0.2, 0.5, and 0.5, respectively. Sensor placement is at 0.80 m above the floor. Thermal comfort is calculated after the energy simulation according to the PMV model developed by Fanger. TCV was defined as being outside the range of -0.5 to 0.5 in the PMV index [18]. Recommended TCV values in ASHRAE [20] are below 10%. Examining multiple conflicting goals for building designs is a complex process [21]. Therefore, finally, multi-objective optimization was used in the study, which can help evaluate these goals simultaneously and provide alternatives. Optimization goals are maximizing UDI and minimizing TCV and EUI. Design variables and ranges are set as follows: PBR types from 10% to 100% in 10% increments, WWR from 10% to 95% in 5% increments, Cooling and heating set points are set to range from 23.5 to 27°C and 18 to 23.5°C, respectively, in 0.5°C increments. There are two types of walls: brick and aerated concrete, and the thickness of the wall and insulation material varies.

3 Results and discussions

According to the analysis results of the existing building, the visual comfort indicator UDI (100-2000lx) is 61.81%. While the benefit is seen to be low in front of the windows, probably because it receives more than 2000lux of light, it is at the desired level in the overall space. GA analysis, another indicator, requires annual values for each point and viewing direction. Less than 45% glare for more than 5% of occupied hours is the threshold value for visual comfort for DGP. The average value of GA was 86.36%. It has been observed that during working hours there is a lot of glares in front of the window and no glare inside the room. In terms of thermal comfort, the annual number of uncomfortable hours exceeding 0.5 (i.e. feeling hot) and below -0.5 (i.e. feeling cold) is 234 and 231 hours, respectively. The

uncomfortably hours are 14.90% of the total number of occupied hours during the year.

Regarding energy performance, the total EUI value per m² is 1751.22 kWh/m²y. The amount of electrical energy consumed for lighting is the least and the amount for heating is the highest.

This façade alternative proposes integrating the PBR full of algae growth medium and a double-glazed window with air inside in place of the existing façade. As a result of the optimization, UDI values vary between 53.40-70.09% and EUI values between 487.68-753.22 kWh/m²y, while TCV values vary between 5.13%-17.98%. Table 2 exhibits that the WWR ranged between 30-40% in algae concentrations of 10%; between 25-40% in algae concentrations of %20 and between 30-40% in 60% concentration. This situation coincides with the studies conducted in the same climate in literature. Giouri et al. [22] stated that small-sized windows in an

office building in a Mediterranean climate have a positive effect on reducing energy demand as well as increasing the comfort level in a building, since they cause solar heat gains and therefore cooling loads to decrease. In addition, although the increase in algae concentration decreases the UDI, it also reduces uncomfortable hours.

The highest UDI value (70.09%) among the optimal solutions was in PBR. with algae concentration 10% at 40% WWR. However, the fact that both the EUI value and the TCV value are higher than the desired values caused it to not be one of the best options according to the fitness function. Since high WWR leads to an increase in heat transfer and solar radiation, it also increases the energy consumed for heating and cooling. The increase in UDI reduces the energy consumed for artificial lighting. As far as the effect of FBR façade on interior glare is concerned it was seen that all results were above 90%.

Table 2. Selected pareto-optimal solutions.

WWR (%)	PBR type	Wall type-thickness (cm)	Insulation thickness (cm)	Cooling-Heating Set Point(°C)	UDI (%)	EUI (kWh/m ² y)	TCV (%)	Cooling (kWh/m ² y)	Heating (kWh/m ² y)	Lighting (kWh/m ² y)
30	10%	Brick 13.5	10	23.5- 23.5	67.41	570.49	11.09	38.33	527.79	4.37
30	10%	ACB 10	10	23.5- 23.5	67.41	570.00	11.22	38.39	527.23	4.37
30	10%	Brick 10	10	23.5- 23.5	67.41	570.63	11.28	38.37	527.89	4.37
35	10%	Brick 13.5	10	23.5- 23.5	69.88	656.34	14.71	42.81	609.44	4.09
35	10%	Brick 10	10	23.5- 23.5	69.88	656.46	15.03	42.85	609.53	4.09
30	20%	Brick 25	10	23.5- 23.5	64.14	574.43	8.21	37.65	531.38	5.41
30	20%	ACB 19	7	23.5- 23.5	64.14	574.37	8.37	37.75	531.21	5.41
40	20%	ACB 19	12	23.5- 23	69.06	703.31	15.71	46.25	652.60	4.46
40	20%	ACB 17.5	12	23.5- 23	69.06	703.35	15.74	46.26	652.63	4.46
40	10%	Brick 10	12	23.5- 23.5	70.09	742.07	17.98	47.15	690.93	3.99
25	20%	ACB 19	12	23.5- 23.5	57.23	487.68	5.13	33.44	447.93	6.31
25	20%	ACB 19	7	23.5- 23.5	57.23	488.27	5.38	33.54	448.42	6.31

There are many TCV values below 10%, and above 10% are also numerous. High WWR and different heating set points were effective in this. In addition, Table 2 displays that as WWR increases, choosing PBRs with low SHGC prevents overheating and reduces uncomfortable hours. However, this causes the UDI to decrease. Choosing WWR 20-30% for 20% algae concentration ensures that thermal comfort is good.

Table 3 compares all the solutions and the existing building. For visual comfort, daylight benefits are not obtained in many solutions, the algae medium can prevent the discomfort caused by glare. It can be thought that glare will increase when the WWR increases, yet this can be prevented by increasing the algae concentration. As the algae concentration increased in

the same WWR, the daylight distribution worsened due to the decrease in the daylight entering the interior. Moreover, as the WWR increases, the algae concentration increases, allowing the excess light to be filtered. For this reason, some studies propose to make use of PBR as a shading element. For example, Pagliolico et al. [23] investigated plastic bag PBRs that can be easily installed. While Talaei et al. [24] proposes that users can change the algae amount inside a flat plate PBR in response to their needs. Energy performance has at least 59.99% improvement, except for solutions where thermal comfort do not improve. The energy demand for heating is significantly higher than the energy demand for cooling. This is because, the solutions with higher thermal comfort require high

heating setpoints, which corresponds to higher heating loads. It has been observed that it helps to reduce uncomfortable hours spent feeling especially cold in

thermal comfort. The energy from burning algal biomass does not make up for a high percentage of the building loads.

Table 3. Summary of analysis of the pareto-optimal solutions.

WWR (%)	PBR type	UDI (%)	Improvement (from 61.71%)	GA (%)	Improvement (from 86.30%)	EUI (kWh/m ² y)	Improvement (from 1751.22 kWh/m ² y)	TCV (%)	Improvement (from 14.70%)
30	10%	67.41	+9.23	95.07	+10.09	570.49	+67.42	11.09	+24.56
30	10%	67.41	+9.23	95.07	+10.09	570.00	+67.45	11.22	+23.69
30	10%	67.41	+9.23	95.07	+9.04	570.63	+67.42	11.28	+23.25
35	10%	69.88	+13.24	94.17	+9.04	656.34	+62.52	14.71	-0.08
35	10%	69.88	+13.24	94.17	+11.12	656.46	+62.51	15.03	-2.26
30	20%	64.14	+3.94	95.96	+11.12	574.43	+67.20	8.21	+44.18
30	20%	64.14	+3.94	95.96	+9.32	574.37	+67.20	8.37	+43.09
40	20%	69.06	+11.91	94.41	+9.32	703.31	+59.84	15.71	-6.84
40	20%	69.06	+11.91	94.41	+8.01	703.35	+59.84	15.74	-7.06
40	10%	70.09	+13.58	93.28	+11.97	742.07	+57.63	17.98	-22.32
25	20%	57.23	-7.27	96.7	+11.97	487.68	+72.15	5.13	+65.11
25	20%	57.23	-7.27	96.7	+11.97	488.27	+72.12	5.38	+63.37

4 Conclusion

For building retrofits there is a need for innovative products that reduce carbon emissions and when possible, have other environmental benefits. This paper focused on PBRs integrated to retrofit the building envelope and investigated them with building simulation and optimization. The primary results are: The heating and cooling setpoints were the most effective design parameters in determining EUI. The algae density inside the PBR affected the TCV the most. It shaded indoors and resulted in overall fewer discomfort hours. For UDI, optimal results were when the algae density inside the PBR was mostly either 10% or 20%. Higher densities resulted in lower UDIs. The PBR decreased glare in all cases. The DGP can be adjusted with the algae density inside the PBR. This work adds to the body of knowledge on PBR façade applications by using it with windows. A model validated with full-scale experiments, life cycle analysis and researching more beneficial ways to use algae in further studies can be the next step for improvement. While more research is necessary to realize PBR retrofits, preliminary results show promise.

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