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Energy Use and Lighting of Algal Green Buildings

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Abstract: Green buildings can provide a growth environment for microalgae growth on their façades, where a closed environment mimicks the organisms' natural environment and functions as a window. This study investigates such a façade's effect on energy saving by optimizing the performances of useful daylight illuminance (UDI) and energy use intensity (EUI) in the Mediterranean climate. The study was carried out in two stages. The first stage is a parametric study using the Colibri tool to look at the algae content and the effect of WWR for the north and south orientations. Meanwhile the second stage adds different design parameters of orientation, window type, WWR, wall type and thickness, insulation thickness. Optimization of UDI and EUI separately allows an in-depth discussion of these parameters for both performances. The obtained parametric results show the effects of WWR and algae content. Regression analysis explains that WWR has a linear relationship with EUI and a polynomial relationship with UDI. There is no such relationship for algae content, yet it changes UDI results the most (%46.22-81.66 for 50% WWR). Then, computational simulations regard effects of other factors for performance optimization.

1. Introduction

Ensuring maximum user comfort with minimum energy consumption is amongst the primary objectives in the building sector. In the research for a more sustainable and green buildings, a photobioreactor (PBR) can be used as a double window with fluid, i.e., growth medium with algae mixture inside. It affects the energy balance of a building in various ways. First, it changes the facade's light transmission, related to the algal content [1]. Second, the PBR window element provides an additional thermal mass to the adjacent space [2] or can heat water and the spaces [3]. Third, the biomass produced from the algae can generate energy or bring different side benefits [4], including biofuel production [5] and carbon sequestration [6]. However, the cost of this PBR element to reach these benefits is a limiting factor, and the benefits need optimization for a building application. Nevertheless, this application can create lesser environmental sustainability concerns for microalgae-based industrial applications as discussed by [7].

The window is the building envelope component whose total heat transfer coefficient is normally five times greater than other components of the building envelope and is responsible for 60% of a building's total energy consumption [8]. Therefore, the correct design of windows is important for the building's energy consumption. At the same time, improving building performance requires evaluating multiple parameter combinations. Green buildings require better energy performance than business as usual scenarios. The energy consumed in buildings can be evaluated in various ways for different purposes (for example heating, cooling, lighting) and user profiles and requirements. Therefore, EUI, which shows the annual energy consumption per unit area, is a key performance indicator for the evaluation of green buildings' operations [9]. Since daylight dynamically changes within a space, it is hard to say that a space has enough daylight for the occupant's health and wellbeing in a green building. UDI is the ratio of useful daylight hours to all the daylight hours the building is in use and is used to perform analysis for green buildings [10]. However, the daylighting and heating/cooling energy requirements show contradictory requirements in the Mediterranean climate. Therefore, balancing them while balancing comfort is essential.

The PBR is not a standard building element. Hence, a validated model for this evaluation does not exist. Stevanović [11] stated, it is necessary to determine which parameters affect the building performance and use energy-efficient design strategies to maximize building performance. To improve building performances, finding the optimum solution within the design variables can be achieved with optimization platforms combined with building simulation tools. Optimization methods produce various solutions. In a single-objective optimization, solutions are ranked from best to worst while a multi-objective optimization offers

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optimal options. Although the most significant limitation of single-objective simulations compared to multi-objective simulations is that it can be challenging to decide before design because it does not consider another purpose, about 53% of the building optimization studies in the literature used single-purpose optimization [12].

In literature, few studies allow for rapid investigation of the effect of the PBR's design on the building performance. Negev et al. [13] used Grasshopper to examine the energy consumption of an office building in Tel Aviv, which has a Mediterranean climate, and found that algae content and window size are statistically significant factors. Taleai et al. [14] investigated a cold arid climate, researched EUI and UDI values for the same PBR windows as Negev et al. [13], and proposed two optimization methods. This study aims to investigate the effect of PBR application on energy consumption and indoor daylighting requirements by energy use intensity (EUI) and useful daylight illuminance (UDI) metrics for an office building with a Mediterranean climate. The separate evaluation of the effect of PBR systems on energy and daylight performance allows for an in-depth discussion of different design features.

2. Materials and Methods

This procedure investigates the effects of orientation and type of glazing on energy consumption and daylight illumination. The glazing type change reflects either the use of different window glazing or PBR with different algal content, in other words with different visual transmittance and solar heat gain coefficient values. This effect can be compared to using different window films in an office building as discussed by [15], when higher algal content decreases visual transmittance. The weather data file for İzmir, Güzelyalı that contains 1950 to 2011 data was downloaded from ladybugtool/epwmaps [16]. The computational model uses different tools holistically and comprises three basic steps. Step one is parametric design modelling in Rhinoceros Grasshopper.

Table 1. Design parameters and ranges.

Window Glazing	Visual Transmittance	Solar Heat Gain Coefficient
Double glazing	0.76	0.81
Water wall	0.84	0.82
%20 algal content	0.45	0.40
%30 algal content	0.33	0.30
%40 algal content	0.17	0.20
%50 algal content	0.14	0.16
%60 algal content	0.11	0.13
%70 algal content	0.08	0.11
%85 algal content	0.06	0.09
%100 algal content	0.04	0.07

The second step is running daylight and energy simulations. Ladybug and Honeybee plugins use the EnergyPlus and Radiance/Daysim engines. The link between daylight and energy simulations transfers the daylight results, thus enabling the calculation of energy savings from daylight.

In this study, the metrics of UDI and EUI assess the PBR element's performance. Therefore, metrics are invaluable. A significant metric for a translucent element is the UDI, in which the lighting control system is set to switch off with automatic dimming according to the occupancy sensor. UDI is the percentage of occupied time within a target illuminance range. Many studies use the values less than 100 lux is not usable enough and more than 2000 lux provide glare. useful [17]. Therefore, this study also considers daylighting levels between 100 and 2000 lux. Besides, EUI expresses the annual total energy requirement per unit area.

Parametric simulations were carried out with the Colibri tool to better understand the effect of WWR and algae content on UDI and EUI. This plugin in Grasshopper allows seeing all the possibilities by trying all the alternatives within the parameters. Parametric studies with Colibri were for the north and south directions.

As the number of possibilities increases, the simulation time increases. Therefore, all simulation elements except for WWR and window type are kept constant. In other words, the WWR varied from 10% to 95% in 5% increments. Window type depended on algae content is set to 20%, 30%,40%, 50%, 60%, 70%, 85% and 100% (Table 1). While evaluating the effects of two parameters on energy and visual comfort, the heating setpoint is 18°C, and the cooling setpoint is 23.5°C. The wall type-thickness is 19 cm aerated concrete, and the rockwool insulation thickness is 10 cm.

The third step is to optimize the results with the Galapagos plugin. For EUI the optimization criteria is the lowest possible value that corresponds to the minimum energy consumption. As for UDI, finding the highest ratio of useful hours is necessary. While the criteria differ, the process for finding the optimum value is the same. It is the use of the Galapagos optimization plugin. The Galapagos plugin is an optimization tool based on evolutionary algorithms in Grasshopper for single-purpose optimization problems.

First, the strings encode all potential solutions in the parameters during the usage. The simulation starts with a random solution set. Then, it calculates a fitness value for each string to show the solution quality of the sequences. Later, a random selection of a group of sequences occurs according to a particular probability value for multiplication. The crossover and mutation processes continue for the predetermined number of generations or when the results become steady, corresponding to the fitness values of the new individuals. The objective function determines the selection of the most suitable sequence. In this study, Galapagos optimizes the parameters of EUI and UDI by separately solving them.

3. Results and discussion

During simulation, the Galapagos interface visualizes the fitness function and marks the best solutions with a + sign on the upper side of the interface. Meanwhile, the lower side displays a clustering of individuals (lower left), the potential solutions for each parameter (lower center), and the best fitness functions with gene sequences for each generation (lower right) (Figures 3 and 5).

3.1. Parametric study of algae content and window to wall ratio (WWR)

UDI and EUI graphs are given for window to wall ratio (WWR) of the PBR positioned to the north in Fig. 1, and results for the south orientation are in Fig. 2. An examination of window type shows that UDI increases in the water wall up to 20% window opening in the north direction, while it decreases in larger openings and it shows the same trend in the south direction.

The effect of WWR on the UDI indicate that the UDI increases as the WWR increases for the north direction. Regression analysis shows that WWR has a polynomial relation with UDI. In PBRs with high algae content, daylight cannot be utilized because the amount of light entering will be less in small openings.

EUI results show that energy use increases as WWR increases in all window types (Figure 1). Regression analysis confirms that WWR has a linear relationship with EUI. As the WWR increases, the heat loss or gain becomes higher. For this reason, low WWRs are preferable to lower energy consumption for both orientations. However, although consuming the least energy is desirable, there should be a lower limit in the WWR to benefit from daylight.

WWR can affect both UDI and EUI performance metrics. Choosing WWR in the right proportions is essential to meet both objectives. Also, the window type with lower window opening and low algae content can meet both performances for both directions. For algae content higher than 40%, a significant decrease ensues between 40% WWR to 45%. This change is due to the transition of window geometry from horizontal to having more height. Kharvari [18] also observed this geometric effect. Thus, UDI and EUI decreased between 40% to 45% WWR and increased after 50% WWR.

When looking to the north, the UDI value is zero after 50% algae content. Although WWR increases, daylight could not be utilized because the light transmittance decrease due to the increase in algal content. PBR with 80% algae culture allows higher algal content to be used in the design than the filled PBR. Likewise, although it is not zero after 50% algae content, there is a significant decrease in UDI in the south direction.

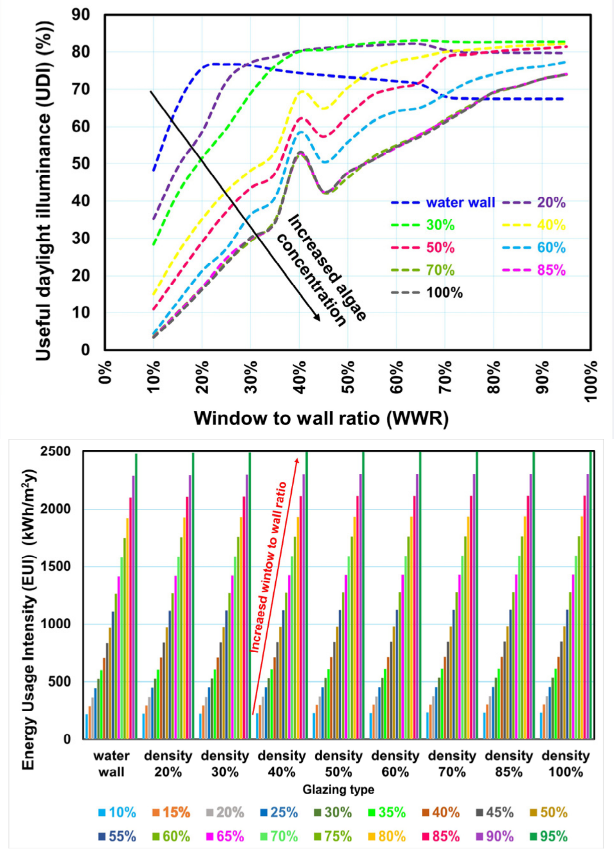

Fig. 1. Performance of UDI by WWR and EUI by window type for the north orientation.

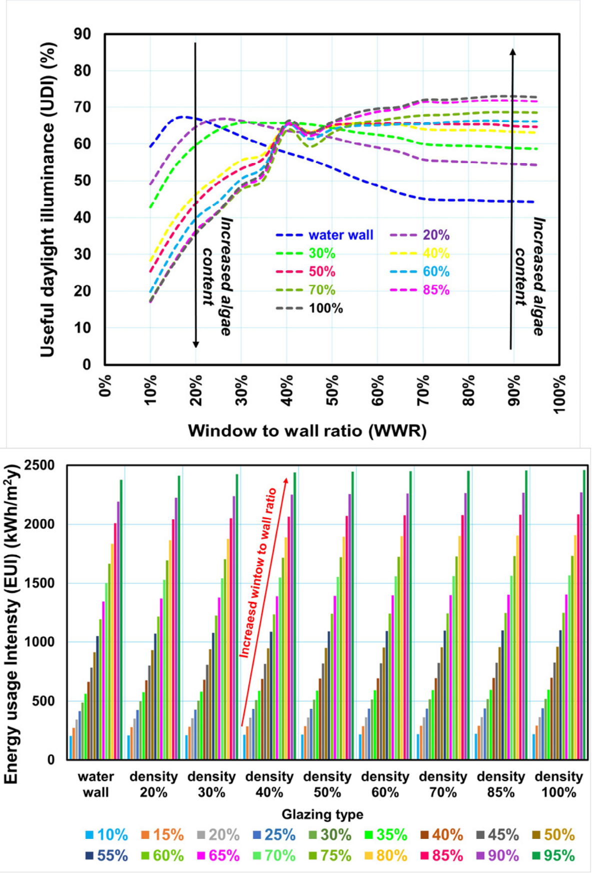

Fig. 2. Performance of UDI by WWR and EUI by window type for the south orientation.

3.2. UDI optimization

To achieve the highest UDI requires the fitness function in the evolutionary solution to be the maximum. The optimization worked for 30 generations in 100% geometry. Fig. 3 shows that the optimization stabilized after the 4th generation.

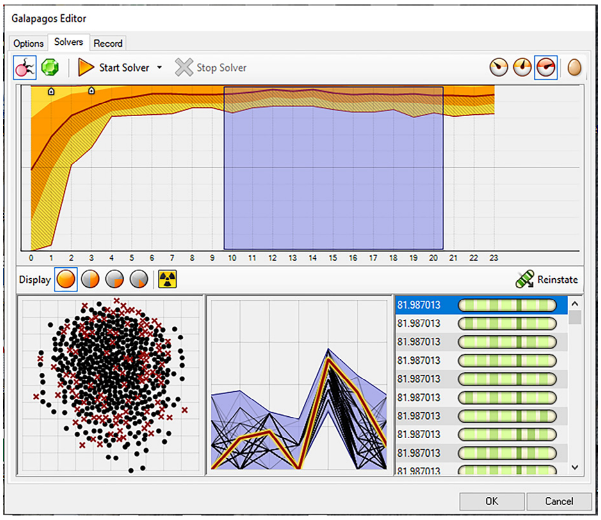

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Fig. 3. Galapagos optimization results for UDI.

The best UDI for the north orientation is 20% algae content and 65% WWR. The best UDI values change between 81.98% and 76.45%. As algae content increases (while keeping the orientation and WWR constant), UDI decreases, and EUI increases. The UDI is 80.97% for 20% algae content, and a 50% WWR positioned in the north direction, while it is 79.1% when a building with the same configuration has 30% algae content.

The UDI value increases as the WWR increases when positioned north at the same algae content. However, after 70%, UDI decreases. Similar UDI change applies to both geometries.

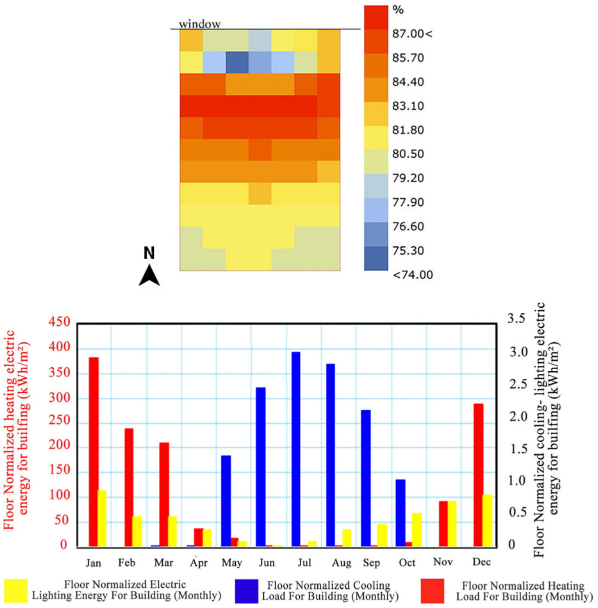

Fig. 4. Visualization for the best UDI.

The optimum results are the most frequent at 0°(north) and 45° (northwest) orientations. When the orientation changes from 0° to 45°, UDI decreases significantly in a building with the same algae content and WWR. The best UDI value is at 20% algae content. Fig. 4 shows the best solution on the working plane and corresponding EUI values.

3.3. EUI optimization

The fitness function is set to a minimum in the evolutionary solution process to minimize energy usage. Fig. 5 shows the gene map of individuals, visualization of gene parameters, and numerical values of individuals.

Conditions corresponding to the lowest energy consumption value (149.90 kWh/m^2) are south orientation, double glazing, and 10% WWR (Fig. 6). In addition, the corresponding UDI value is 60.16%. The best results are by positioning it in the south direction. The following best orientations are 135° and 225°. While the best values are for double glazing, there are also good values with 20% and 30% algae content.

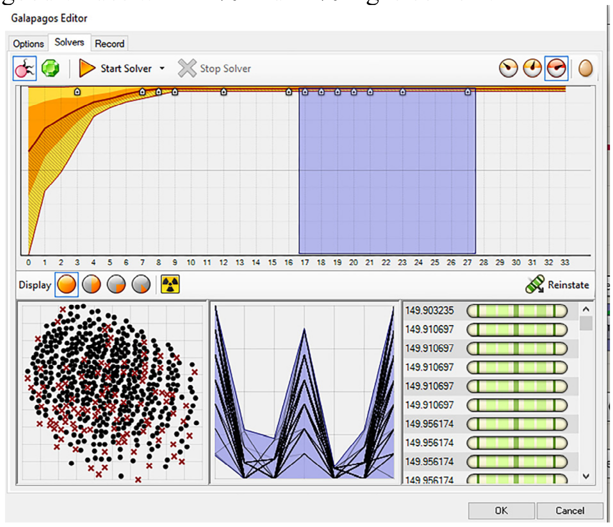

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Fig. 5. Galapagos optimization results for EUI.

The best values are in small window openings to minimize the heat gains caused by larger window areas in the Mediterranean climate. They lead to reduced solar heat gains and therefore reduced cooling loads.

The optimizations determined that brick with high thermal capacity is the most successful for the outer wall.

Examining the effects of wall type, thickness, and insulation thickness indicate that EUI decreases as the wall thickness increases for 10% WWR, double glazing in the south direction. Similarly, with 20% algae content, EUI decreases as the insulation thickness increases. Insulation thickness is a significant parameter for İzmir, where heating and cooling setpoints are generally the same values in the corresponding orientations.

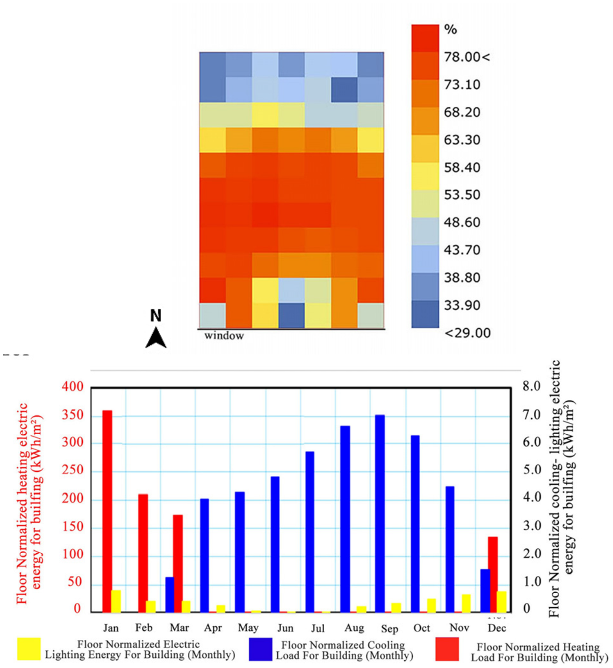

Fig. 6. Visualization for the best EUI.

4. Conclusion

The optimization uses possible design solutions to investigate EUI and UDI values between 100-2000 lx for different orientations, based on different window types, WWR, wall type and thickness, insulation thickness, and heating and cooling setpoints. The optimizations show that the three parameters of orientation, window types and geometry, and WWR affect the UDI. However, the potential energy savings vary depending on all the studied parameters. The factor affecting the performance of the translucent PBR facade most for UDI is the content of the algal mixture. Meanwhile, orientation and WWR affect the EUI.

An evolutionary algorithm optimized the parameters to reach the selected objectives. The purpose of using this algorithm is to have potent benefits and overcome most problems. Unlike many proprietary algorithms, evolutionary solvers provide a never-ending stream of solutions, with new solutions are often of higher quality than previous ones. Also, because the runtime process is gradual, intermediate solutions are obtainable. Since maximum UDI and minimum EUI objectives have conflicting requirements, it is difficult to say that one solution is better than the other. Therefore, future studies will focus on multi-objective optimization of these parameters with genetic algorithms.

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