

Multi-objective evolutionary optimization of photovoltaic glass for thermal, daylight, and energy consideration

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ABSTRACT

The potential of fenestration systems is increased by incorporating photovoltaic technology into windows. This recently developed technology enhances the ability to generate energy from the building façade, improve the thermal and daylight performance of buildings, and visual comfort of occupants. Integrating an evolutionary optimization algorithm into this technology is one of the possible sustainable solutions to enhance building performance and minimize environmental impact. This paper uses a genetic evolutionary optimization algorithm to explore the optimum performance of photovoltaic glass in an architecture studio regarding annual energy consumption, energy generation, and daylight performance. Design variables include a window-to-wall ratio (i.e., window size and location) and amorphous-silicon thin-film solar cell transparency to generate optimum Pareto-front solutions for the case building. Optimization objectives are minimizing annual thermal (i.e., heating and cooling) loads and maximizing Spatial Daylight Autonomy. Optimized results of low-E semi-transparent amorphous-silicon photovoltaic glass applied on the façade show that the spatial daylight autonomy is increased to 82% with reduced glare risk and higher visual comfort for the occupants. Photovoltaic glass helped reduce the selected room's seasonal and annual lighting loads by up to 26.7%. Lastly, compared to non-optimized photovoltaic glass, they provide 23.2% more annual electrical energy.

1. Introduction

The World has been demanding more energy as the industry has grown recently. Significant environmental contamination has occurred by the widespread use of fossil fuels (IEA 2016); [13,15]. Thus, renewable energy has been developed competitively because of the shortage of energy (Meng, Jinjing, Hongxing, et al., 2018). Building-integrated photovoltaic (BIPV) systems, which use solar energy to generate electricity on-site, have been recognized as possible practical ways to enhance energy saving of buildings and minimize environmental impact (EPIA 2011). With the help of BIPV technology, it is possible to use buildings as a source of electrical energy by embedding photovoltaic (PV) materials into the building envelope components [4].

PV systems use solar energy that is absorbed to generate electricity. BIPV is a novel type that has recently emerged on the market. They are connected to the parts of the building (i.e., roof, façade, slab, shading device) instead of a detached component away from the building

envelope to meet some energy needs. Many researchers recommend using these systems for new buildings and renovating existing ones. As a relatively new application, semi-transparent PV glazing has gained the interest of many researchers due to its capacity to generate energy and provide daylighting illumination (Meng, Jinjing, Hongxing, et al., 2018).

Recent studies show that semi-transparent PV cells might increase the building energy efficiency when applied to the glazing [5]. It not only improves buildings' overall performance but can also enhance occupants' thermal and visual comfort. There are various types of semi-transparent thin-film solar cells in the industry. Each performs differently due to its various electrical and optical properties. Several studies have shown their potential, but it is noted in many research that amorphous silicon (a-Si) solar cells are preferable to other types of solar cells. According to the results, it increases energy savings for heating and cooling loads [12]. There are three main research methods to assess the overall performance of PV glazing technology. One may be the utilization of devices that can monitor the real-time performance of these

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Nomenclature

Abbreviations

WWR	Window-to-Wall Ratio
sDA	Spatial Daylight Autonomy
BIPV	Building-integrated Photovoltaic
RES	Renewable Energy Source
a-Si	Amorphous Silicon
EA	Evolutionary Algorithm
GA	Genetic Algorithm

systems. A study aims to understand the potential of PV glazing in terms of energy, daylight, and thermal performance using real-time measurement tools [9]. The brief results show that PV glazing and shading elements can decrease the building's electrical energy consumption and lighting load. A similar study proposed to test monocrystalline silicon solar cells' daylight and energy performance implemented on a PV shading device using field tests and a scale model [18]. Results proposed that architectural variables such as the incline angle and PV implemented area of the shading device significantly affect its performance. With digital tools' development, simulation-based software can be used in such research. They test the performance of any system without using such devices. One related study focuses on the energy, daylight, and aesthetic properties of façade-integrated PVs (FIPV) installed in different balconies in Trondheim, Norway [6]. Simulation, survey, and mathematical methods for users to assess their overall performance. Results propose that side balconies are preferable in terms of daylight performance and energy generation, while partial balcony railings with complementary colors are more desirable in an aesthetical sense. It is noted in the study that FIPV and roof-integrated PVs can cover the energy need of an eleven-story building by up to 60 %. Another study proposes a smart low-E PV glazing system containing a thermotropic layer that changes its visibility and optical properties to prevent overheating inside an office building in Nottingham, UK [36]. The specified PV is tested in thermal, electrical, and optical aspects. Brief results show that BIPV smart windows with different window-to-wall ratios, orientations, and transition temperatures affect the energy-saving potential of a building by up to 36.6 % with higher visual comfort of occupants. A review study analyses different types of PV glazing, such as single and double glazing with or without ventilation. Studies in the literature are reviewed based on their energy generation and thermal performance. Study results indicate that conventional glazing can store more heat in the summer when compared with PV glazing. Also, PV glazing can contribute to the building's energy-saving capacity by reducing the cooling loads in hot climate regions [16]. One study compares PV glass's energy and thermal performance with conventional glazing [35]. Conventional glazing types are single and double pane glazing for this study. The results demonstrate that semi-transparent solar cells applied on windows can decrease total annual electricity consumption by 16 % and 18 % in temperate climates such as Hong Kong. PV glass improves a building's daylight performance together with its energy and thermal efficiency. One study discovered solar glazing could significantly enhance a façade's daylight performance. Also, they offered 26.5 % of energy savings during the winter. According to one research, PV glasses could balance the lighting loads in a room between 15.1 % and 20.3 % [38]. They reduced the risk of overheating, cooling loads, and glare with enhanced occupant thermal and visual comfort. The third method emerges from the optimization approaches in that some studies have developed optimization models to generate optimum BIPV design. A study implemented an asymmetric concentrator PV glazing to the South façade of a building to enhance its energy generation and daylight performance. Experimental models have been created to assess its performance [30]. An optimization model has been developed to reduce the

shading effect of each concentration array. The study variables are the gaps of concentrators, and the objectives are high optical quality, daylight, and energy performance. The optimization model indicates a suitable asymmetric concentrator PV glazing on the South façade of the building. A related study proposes assessing four different BIPVs' energy performance in three different climatic zones [26]. Thermal and visual comfort simulations are conducted through TRNSYS software. Results proposed that BIPV technology greatly impacts achieving zero-energy buildings. The optimization process has achieved an energy saving of up to 43 %. The BIPV flexibility index is increased to 0.57 for varied climate regions. Indoor thermal and visual comfort are increased to 54 % and 83 %, respectively. An initiative study proposes an optimized model for façade integrated BIPVs in an office building in Gyeonggi-Do, Korea [33]. Brief study results show that BIPV can cover the need for building electricity in a range of 1-and 5 % if optimization is applied to the performance objectives (Chae, Kim, Park, et al. 2014). BIPV systems are unique because they perform differently in varied climatic areas. One related work tests PV glass's thermal, energy, and daylight performance in diversified regions. It is suggested in the study that PV glass's optical characteristics should be optimized according to the climate. A similar study focused on optimizing different BIPV shading system configurations to maximize solar irradiation (Freitas and Brito 2015). It is found in the results that a tilted louver can produce up to 40 % more electrical energy compared to a standard flat and vertical shading device. A recent study investigates the effect of different glazing types and window sizes on daylight performance and energy efficiency for an office building in Algeria (Mesloub, Albaqawy, and Kandar 2020). Double-glazing PV modules with a 20 % window-to-wall ratio are considered optimal PV windows. They provided 60 % energy saving for the south façade.

Integrating new technology RESs into buildings with optimization algorithms was one of the possible sustainable solutions to increase building energy saving [34]. The optimization algorithm seeks to find the optimal solution. In a numerical sense, achieving the maximum or minimum value for different building variables is the procedure. Building performance optimization works with several design variables. Single or multi-objective optimization procedures are applied according to the number of objectives in the studies. Two methods can be preferred in multi-objective optimization problems. One is the weighted sum model, and the other is the Pareto front optimization method. Pareto optimization aims to find the trade-off or Pareto front between different building performance metrics or objectives. It seeks to dominate each genome objective (i.e., the solutions) (Evins 2013). Broadly two optimization methods used in the studies: conventional and computational optimizations. Both can be used for performative computational architecture (PCA). Conventional optimization methods analyze predefined design variables, while computational optimization methods work with optimization algorithms to achieve suitable building performance [3]. There is the evolutionary algorithm (EA) in the context of computational optimizations. It is also called population-based optimization. EAs work with populations of solutions to optimization problems. The population evolves into better candidates (Simon 2013). As a sub-class of evolutionary algorithms, there is a genetic algorithm (GA), a heuristic optimization method. It is a biological evolution's natural selection process (Galletly 1998). GA is based on biologically inspired variables, selection, mutation, and crossover to develop outstanding ideal generations for optimization tasks. The population generates an ideal solution as the GA arbitrarily selects good-performing solutions from the current population and employs them as parents to construct the next generation (MathWorks 2016). GA can solve complex design problems and multi-objective optimizations and eliminate failure rates due to simulation (Nguyen, Reiter, and Rigo 2014). Architectural decisions are significant in the design phase of buildings since they influence the building's performance [19]. Optimization algorithms provide practical guidance for the conceptual design of a project [31]. They also allow for saving costs and time for architects by providing guidance. Simulations are essential in most daylight and energy studies. Thus, the optimization

process assesses many design decisions without simulating them manually.

Although studies in recent literature mainly concentrate on efficiency of PV glass and their effect on improvement on building performance, the target of this study is to discover the rate of coupling impact of PV glasses on an existing room in terms of heating, cooling and lighting loads together and visual comfort requirements in a comprehensive approach. We assume this study is a trial renovation project, including shifting the existing glazing with the PV ones and revising the window areas. Thus, we aim to understand whether the power generated from PV glasses can match the lighting loads of that room (studio) after renovation. This is significant since the optical modification in glasses alters the passage of daylight inside. In this sense, the study contributes an original perspective to the literature. It uses digital and manual tools to analyze and validate the results and obtain broad conclusions on using this technology in such a building.

This study focuses on multiple energy efficiency and visual comfort aspects (i.e., daylight performance, energy consumption, and PV energy generation) rather than concentrating on a single performance object. Also, multiple architectural design decisions such as window size, location, and PV glass transparency are widely explored using Octopus genetic optimization algorithm. For these reasons, the study concentrates on many aspects, optimizing an architecture studio of Izmir Institute of Technology Campus in İzmir, Turkey, for energy saving, energy generation, and enhancing daylight performance with visual and thermal comfort of occupants. The paper seeks to understand the potential of PV technology based on the building's annual heating and cooling loads and the selected reference room's Spatial Daylight Autonomy (sDA).

2. Method

2.1. Research framework

The study's first phase includes energy and daylight analyses of the base case and experimental case with PV glass. For the first step, the base case, an existing architecture building, is short-term monitored to understand the building's thermal behaviour and calibrate the energy simulation model. The building is algorithmically modeled in a Rhino/Grasshopper environment to conduct daylight and energy simulations. Grasshopper and its plug-ins enable researchers to conduct algorithmic-based performance analysis. There are several tools to conduct performance-based simulations for indoor environments. These are mainly divided into two: algorithmic-based tools and regular tools. In terms of the algorithmic ones, it is practical to use these analytic tools that give the generative process exact feedback by employing a parametric model in which formal generation rules are converted into an algorithm. Therefore, analysis can actively participate in the process of creating the architectural form [40]. Some of the algorithmic performance modeling tools are Grasshopper, Dynamo, Ecotect, EnergyPlus, Radiance, Daysim, and OpenStudio. A visual algorithm editor called Grasshopper, also used in this research, creates parametric and algorithmic models on the modeling software Rhinoceros (Rhinoceros 3D 2023). Grasshopper enables engineers and architects to create design algorithms by constructing them on the rule- and parametric-based systems. Several energy analysis-specific plug-ins, including GECO, Diva for Rhino, and Ladybug, expand Grasshopper's programming capabilities and compatibility with other analysis programs. This research uses Ladybug tools to conduct performance-based analysis. Besides algorithmic tools, some of the other examples of indoor performance (i.e., daylight, energy and comfort) simulation tools can be given as DesignBuilder, DOE2, TRNSYS, Relux, DIALux, SAM, etc. (Pan et al. 2023). DesignBuilder is used for research and consultancy since it enables the combined analysis of indoor climate and energy consumption in buildings. It is built on a modular platform equipped with a graphical modeler and an engine calculation, making it possible to add further

components using the Neutral Model Format (NMF) and Modelica language. DesignBuilder uses EnergyPlus as the simulation engine to compute the simulations. Some other tools, such as Grasshopper plug-ins, Ladybug and Honeybee, use EnergyPlus for energy estimations. It is a simulation engine that solely uses text files for input and output, which suggests the necessity for a separate graphical user interface [41]. The validation of building energy performance tools is one of the most studied topics. Significant performance differences between simulations and measurements are reported in several articles [42]. Some of the reasons for these differences are due to improper building materials, schedules, and specifications given to the software. In this research, these are carefully introduced to the special plug-ins of Grasshopper.

In this research, Honeybee, with the Radiance engine, runs daylight simulations. It calculates the architecture studio's Spatial Daylight Autonomy (sDA) as the performance output. Honeybee with OpenStudio conducts energy simulations and computes the building's annual heating and cooling loads in kWh. The Honeybee is a child of the Ladybug family, a special plug-in of Grasshopper. It performs algorithmically building performance-based simulations (food4Rhino 2022). In the third step, the same plug-ins calculated energy consumption, daylight performance, and electrical energy generation of the experimental case with the implementation of PV glass. The base case model involved double-glazed windows, while the experimental case involved low-E PV glass with 30 % transmittance. The simulation engine calculated the seasonal and annual electrical energy generation from PV glass. The second phase implies the optimization process. The Octopus multi-objective optimization plug-in of Grasshopper optimizes the window-based variables of PV glass (i.e., window size, location, and transparency) to obtain minimum heating and cooling load and at least 50 % of sDA. Octopus plug-in plots the results in a three-dimensional axis. The results are examined based on this axis. Output genomes with at least 50 % of sDA and minimum total thermal loads are selected and defined as possible Pareto-front results. These are reviewed based on their energy generation, daylight, and energy performance. Then, the study continues with the selection of the best Pareto-front results. Annual lighting loads are calculated for the best-performed Pareto-front genomes. This analysis is due to evaluating the overall performance of optimized models and seeing the performance potential of the architecture studio. Fig. 1 shows the flowchart of the study.

2.2. Climate

The reference building is in the city of İzmir, Turkey, having a Mediterranean climate. Köppen-Geiger Climate Classification system defines İzmir's climate as hot and dry in summer and rainy and warm in winter. This system is seen as one of the most valuable climates specification systems. Köppen classifies the climates into five groups. These are labeled with letters A, B, C, D, and E. These correspond to tropical, dry, temperate, continental, and polar climates. İzmir is defined as Csa with a hot Mediterranean climate [7].

The EnergyPlus weather data of İzmir is used to assess the climate of the city. The file was then introduced to Climate Consultant 6.0 software to generate radiation and illumination weather data and climate-based information presented in Table 1, Table 2, and Fig. 2 below. Fig. 3 below indicates the sun path chart of the case building, with the aerial photo showing the surrounding rural context.

2.3. The architecture studio

An architecture studio of the Faculty of Architecture is located on the Izmir Institute of Technology Campus, in Izmir, Turkey. The building is in a suburban area with low-rise buildings and a non-urban region in the city (Fig. 4). The studio's size is 210 m², located on the first floor of a three-story building and oriented towards the South and East. It has highly illuminated parts in near-window areas, which cause glare and overheating problems. However, the very back parts of the studio suffer

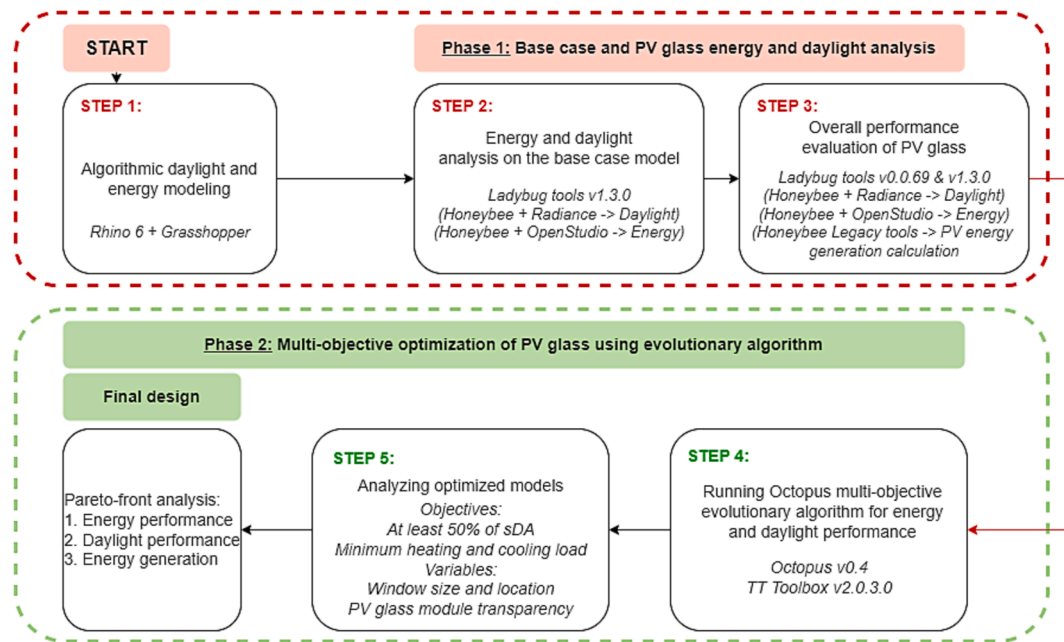


Fig. 1. Research flowchart.

Table 1

The weather conditions and locations of the selected building.

City	Climate zone	Location	Altitude	Summer temperature	Winter temperature
İzmir	Hot summer and warm winter Köppen Climate Specification: Csa	38.31 N 26.63 E	42 m	Average: 27.4 °C	Average: 9.5 °C

from daylight which may result in students being productive during the classes. Visual comfort and glare-related problems generally affect the studio's energy, thermal, and daylight performance during the year.

2.4. Simulation models

2.4.1. Daylight simulation model

Ladybug, a special plug-in of Grasshopper, runs the daylight simulations of this study. Ladybug has been considered as the *parent* plug-in. It has several children to conduct different types of simulations. Honeybee is one of the most widely used children for daylight, thermal, and energy simulations. It uses Radiance as the engine to compute the simulations [1]. The architecture studio is algorithmically and three-

Table 2

Annual radiation and illumination weather data of İzmir, Turkey.

File	Global horizontal radiation (Wh/m ²)	Direct normal radiation (Wh/m ²)	Diffuse radiation (Wh/m ²)	Global horizontal illumination (lux)	Direct normal illumination (lux)
TUR_Izmir.172180_IWEC	399.1	493.5	103.6	21,315	49,693

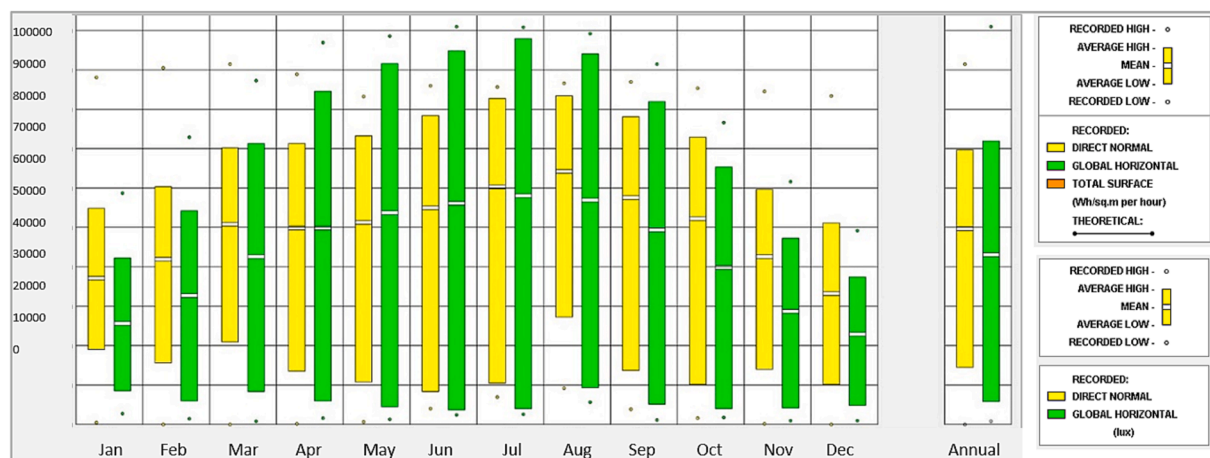


Fig. 2. Hourly illumination of direct normal and global horizontal in lux.

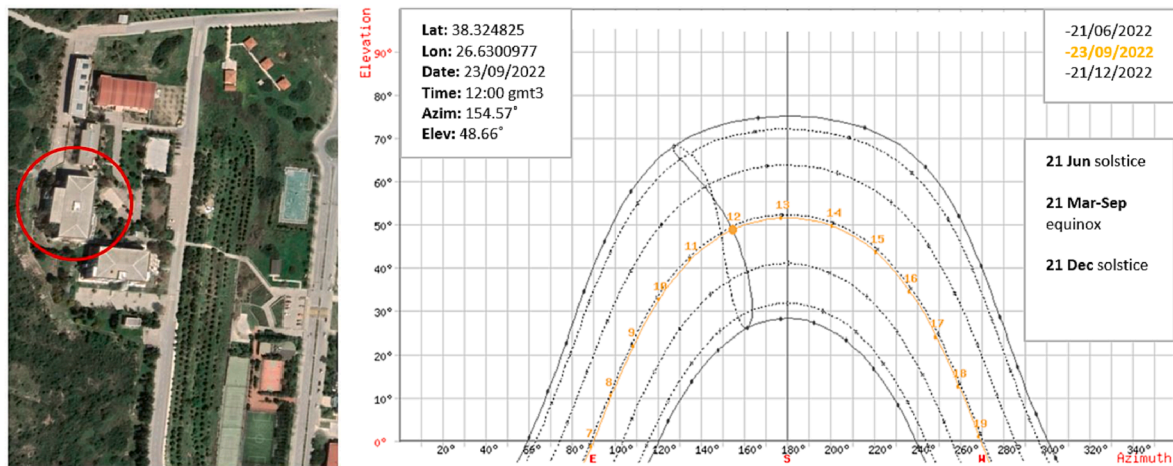


Fig. 3. (a) Location of case building on the aerial view (b) Sun path diagram with the indication of the case building.



Fig. 4. (a) Case building and an indication of the selected studio (b) Plan drawing of the building with the indication of the selected studio in a yellow hatch. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

dimensionally modeled in Rhino/Grasshopper environment. Solid surface materials (i.e., floor, ceiling, and walls) and window properties are assigned to the simulation engine, as seen in Table 3. The engine uses the accurate weather file of Izmir, as explained in Section 2.2, for proper calculations. It runs the simulations annually, with an illuminance-based output, Spatial Daylight Autonomy (sDA). sDA defines the annual simulation area percentage exceeding the minimum illumination level for operating hours [20]. Honeybee uses threshold values to conduct annual illuminance-based task simulations. These are $-t$ for the daylight autonomy threshold, $-lt$ for the lower threshold for useful daylight illuminance, and $-up$ for the upper threshold. These are specified as 500, 300, and 2000 lx, respectively. The measuring grid size for the simulation tests is 0.6×0.6 m, and it is 0.75 m above the ground surface of the studio.

2.4.2. Energy simulation model

Monitoring and calibration procedures are applied to the energy simulation model to obtain a validated simulation model. One week of monitoring of indoor and outdoor temperature, relative humidity, and illuminance level is conducted for the studio [38]. Then, a calibration

process is applied to the simulation models. MBEs and CV(RMSE), two different error indicators (e.g., -3.78 % and 6.3 %, respectively) are computed, and thus the model is accepted as calibrated [38]. During the calibration, some modifications are applied on the epw file according to the outdoor monitored data. Similar to daylight, Honeybee computed the energy simulations. However, the simulations are conducted for the whole building instead of only the case room. Honeybee uses OpenStudio and EnergyPlus as engines to conduct the simulations. The algorithm uses accurate EnergyPlus weather data -the same as used for daylight simulations-, building envelope materials (i.e., wall, ceiling, roof, slab, and windows), building program, occupancy, lighting, electrical equipment, and natural ventilation schedules, HVAC system properties, and surrounding buildings and trees for the shading effect. Envelope material properties are presented in Table 4. Thirty-five architecture students use the studio during the weekdays of the year, between 9:00 a.m.-06:00p.m. Their physical activity is *seated* in the studios and *walking* in the corridors. Computers in the studio become possible heat gain sources. All the doors in the building are kept closed. There are forty led panels in the studio with a 31-Watt for each. Natural ventilation is applied for the studios and corridors according to a temperature schedule. Maximum indoor and minimum outdoor temperatures are 21 °C and 30 °C, respectively. The infiltration level of the building is 0.0004 flow per exterior surface area. This value designates an average tightness. A VRF HVAC system heats the whole building besides corridors and toilets. It starts to heat the building when the interior temperature is below 21 °C and cools when it exceeds 24 °C. All these setpoint values are based on ASHRAE Standards [2]. The simulation engine calculates the shadow effect of surrounding buildings and trees

Table 3
The surface material specifications for the daylight simulations.

Data	Building component			
	Wall	Floor	Ceiling	Window
Reflectance	0.6	0.8	0.65	Double-glazed window with 75 %
Specularity	0	0	0.1	transparency
Roughness	0	0	0.02	

Table 4
Building envelope materials for the Honeybee energy model.

Building component	Type	Layer name	Conductivity (W/mK)	Specific heat (J/kgK)	Density (kg/m ³)	Thickness (m)	U-value (W/m ² K)
External/ ground floor	Typical reinforced concrete floor	Painted metal	45	410	7690	0.0015	0.454
		Ceiling air gap	0.556	1000	1.28	0.1	
		Insulation	0.03	1210	43	0.05	
		Reinforced concrete	0.53	840	1280	0.1	
Exterior wall	Generic exterior wall	Brick	0.9	790	1920	0.1	0.423
		Lightweight reinforced concrete	0.53	840	1280	0.1	
		Insulation	0.03	1210	43	0.05	
		Wall air gap	0.667	1000	1.28	0.1	
		Gypsum board	0.16	1090	800	0.0127	
		Acoustic tile	0.06	590	368	0.02	
Internal floor	Typical interior floor	Ceiling air gap	0.556	1000	1.28	0.1	1.155
		Lightweight reinforced concrete	0.53	840	1280	0.1	
		Insulation	0.03	1210	43	0.05	
		Roof membrane	0.16	1090	800	0.0127	
		Acoustic tile	0.06	590	368	0.02	
Internal wall	Gypsum wall	Gypsum board	0.16	1090	800	0.0127	2.116
		Wall air gap	0.667	1000	1.28	0.1	
		Gypsum board	0.16	1090	800	0.0127	
		Roof membrane	0.16	1210	1120	0.01	
Roof	Typical roof	Insulation	0.03	1210	43	0.05	0.385
		Lightweight reinforced concrete	0.53	840	1280	0.1	
		Ceiling air gap	0.556	1000	1.28	0.1	
		Acoustic tile	0.06	590	368	0.02	
		Insulation	0.03	1210	43	0.05	
		Roof membrane	0.16	1090	800	0.0127	

based on their height, width, and material properties. The Grasshopper script definition is presented in Fig. 5. Honeybee with OpenStudio computed annual heating and cooling loads in kWh for the whole building. Honeybee and its engine EnergyPlus computed the energy generation calculations from PV. All the specifications are introduced to Honeybee, as in Table 7 and Table 8. Annual lighting loads are calculated manually based on simple energy equations (Bayram & Kazanmaz 2020). Although manually calculated lighting loads give a rough estimation, the study does not aim to understand the numerical value of the lighting loads. It aims to understand the change in the results due to variables. The logic is the same in computing the energy simulations. The heat gain from the lighting system is neglected for this study because it is purposed to estimate the change in thermal loads due to the implementations.

2.5. Optimization algorithm

2.5.1. Optimization tool

A genetic optimization algorithm Octopus, a plug-in of Grasshopper, runs the optimization process. Octopus uses SPEA-2 and HypE algorithms [37]. It computed the optimization based on the PV glass implemented model. Table 5 shows some of the optimization specifications in the Octopus interface. Algorithm settings and specifications are necessary because they influence the optimization process and results. First, the optimization type is defined in the navigation part. Pareto-front is selected; however, elite and history solutions are also visible in the three-dimensional axis. Pareto-front solutions are necessary for multi-objective optimization studies because they are the dominant solutions meaning that the algorithm computes and optimizes all objectives with the same priority level.

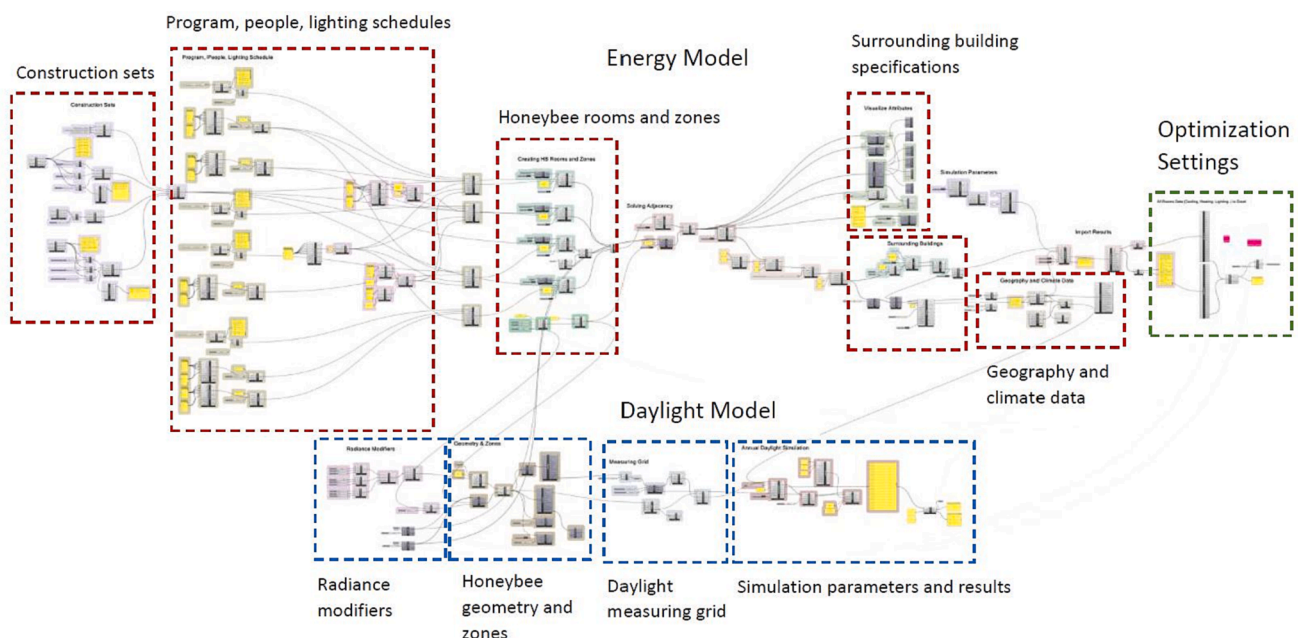


Fig. 5. Grasshopper script for the Honeybee energy and daylight models.

Table 5

Optimization specifications for the Octopus multi-objective optimization algorithm.

Octopus specification	Value
Elitism	0.5
Mutation probability	0.2
Mutation rate	0.9
Crossover rate	0.8
Population size	20
Maximum generations	0

There are some specifications in the Octopus interface related to genetic algorithm logic. The first one of these is Elitism. Instead of the whole pool, Elitism indicates the ratio of new solutions bred from the elite. More local optimization is obtained when it is assigned to a high value. The Octopus defines this as 0.5 (i.e., 50 %) as the default level. There is also the mutation rate that estimates the possibility of every variable or gene being mutated. A low mutation rate indicates minor changes in input variables, while a high rate indicates significant changes. Mutation probability and rate are defined as 0.2 and 0.9 in Octopus. The possibility of two sequentially generated solutions exchanging parameter values is known as the crossover rate. It is set at 0.8 for the study. One influential variable is the population size of an optimization study. Population size is known as the solution number of each generation. There are two variables defined in this optimization study. These are the window-to-wall ratio and glazing transmittance. For two variables, three number strings are defined in the Grasshopper interface. The algorithm selects ten samples for each variable to increase the model feasibility and reduce the complexity of optimization duration, making the population size 30 for only one generation, and the elite size is estimated accordingly. Maximum generation in Octopus is set to 0 as default. It means that there is no end to the research. The Octopus algorithm continued to run until the objectives were at the desired level and a sufficient number of populations had formed. The algorithm ran for a week and then stopped. Then, it generated the results three-dimensionally. Many inputs were entered into the energy and daylight simulation models, increasing one simulation's duration. For this reason, the optimization algorithm had to be run for a week to reach a sufficient number of results.

2.5.2. Variables and objectives

The optimization balances the window-to-wall ratio (i.e., window size and location) and PV glass' transmittance value (Table 6). Octopus algorithm kept the PV glass transmittance between 20 and 40 %. Also, window height is not changed throughout the optimization process, but the width is increased from the center to the wall corners (Fig. 6). There is only one window in each façade. The window does not change its location. Only its width increases from the center to the edges. The objectives are minimum heating and cooling loads and a maximum sDA value. IES defines sDA as "the percent of an analysis area that meets a minimum daylight illuminance level for a specified fraction of the operating hours per year" [20]. According to IES standards, a space requires at least 50 % sDA as an acceptable sDA level. Also, it needs at least 500 lx illumination as the threshold illuminance [8]. This optimization study defines threshold sDA value as $sDA_{500,50\%} \geq 50\%$. It means sDA provides 500 lx illumination for half of the year in at least 50 % of the analysis area.

Table 6

Each variable's value range.

Variable	Range
PV glass transmittance (%)	20–40
Window size and location	same height width increases from the center to the wall corners

3. Results

3.1. Base case analysis

The base case model's daylight and energy performance are evaluated through simulation models. A climate-based daylight performance metric, sDA, is evaluated for the daylight performance of the case room. Daylighting results show that sDA provides at least 500 lx illumination in 59.1 % of the evaluation area in half of the year (i.e., $sDA_{500,50\%} = 59.1\%$) (Fig. 7). Although the study defines threshold sDA value as $sDA_{500,50\%} \geq 50\%$, and the base case model exceeds the threshold level, the studio has visual comfort-related issues that must be addressed in the optimization. The case room does not present a uniform distribution of daylight due to the excessively illuminated parts near window zones and light-dimming parts in the back parts of the room. Simulation results note that at least 2000 lx illumination is available in 13.6 % of the evaluation area in half of the year. Thus, the daylight performance objective of the optimization is to increase the uniform daylight distribution by reducing glare risks and improving light-dimming parts of the room.

Energy performance is evaluated based on annual heating, cooling, and lighting loads. Honeybee uses EnergyPlus and OpenStudio to calculate the whole building's heating and cooling loads. A VRF system heats and cools the building throughout the year. Sanitary areas are not heated or cooled. Honeybee calculated the building's heating and cooling loads as 7,909.507 kWh and 1,114.731 kWh, respectively. The case room's uncomfortable hours for winter, summer, and winter/summer clothes are 877, 1278.5, and 94.75 h, respectively, based on ASHRAE 55–2004 standards. Detailed results can be seen in Table 9.

The annual lighting load (i.e., daily and seasonal energy consumption) is manually estimated for the case room under different sky conditions (i.e., clear sky with sun and overcast sky) using simple energy equations. The equation uses luminaire power, number, and operating hours for daily consumption. Seasonal energy consumption is estimated by multiplying daily energy consumption and the number of days in the season (Fig. 8). The 21st of March, June, December, and the 23rd of September are the representative dates for spring, summer, winter, and fall seasons, respectively. Honeybee computed illuminance-based simulations for 8:00 a.m., 10:00 a.m., 12:00p.m., 3:00p.m., 6:00p.m., and 8:00p.m. Artificial light is used in areas below 300 lx. Students use the studio between 9:00 a.m. and 6:00p.m. during the fall and summer semesters. They occupy it overnight for the spring and winter semesters. The results show that the annual lighting loads are 2453 kWh for a clear sky with sun and 3730 kWh for an overcast sky.

3.2. Selected PV glass performance results

In this section, the study evaluates the daylight, thermal, and energy performance of a-Si thin film solar cells implemented on Low-E PV glass of OnyxSolar © through simulation software (OnyxSolar). The selected PV glass has 30 % transmittance. The study estimates the annual and seasonal electricity generation of PV glass and the annual lighting load of the case room to evaluate the room's overall performance for accurate analysis. The software calculates the building's annual heating and cooling loads, which are evaluated along with the thermal and visual comfort of the occupants. This part of the study aims to understand the performance capacity of PV glass when its properties are not optimized and introduced to the software as manufactured. Tables 7 and 8 present selected PV glass' optical and electrical properties. All these specifications are introduced to Honeybee for PV electrical energy generation calculations. Honeybee uses EnergyPlus as the engine for this type of calculation.

According to the results, selected PV glass provided a 500 lx threshold illuminance level in 28.8 % of the analysis area in half of the year. It is insufficient when compared with the base case model. The glass does not provide visual comfort for the occupants, especially in the

Table 7

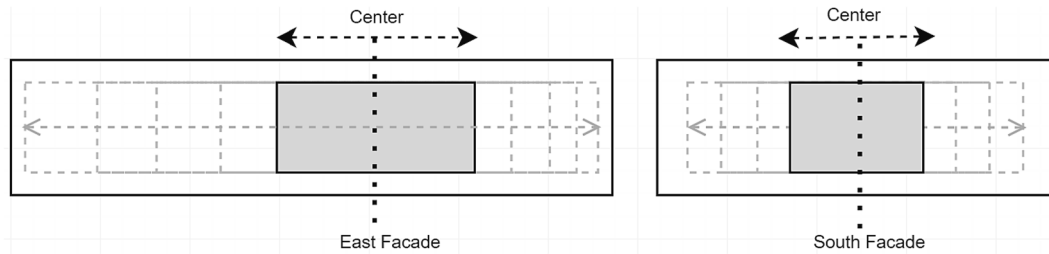
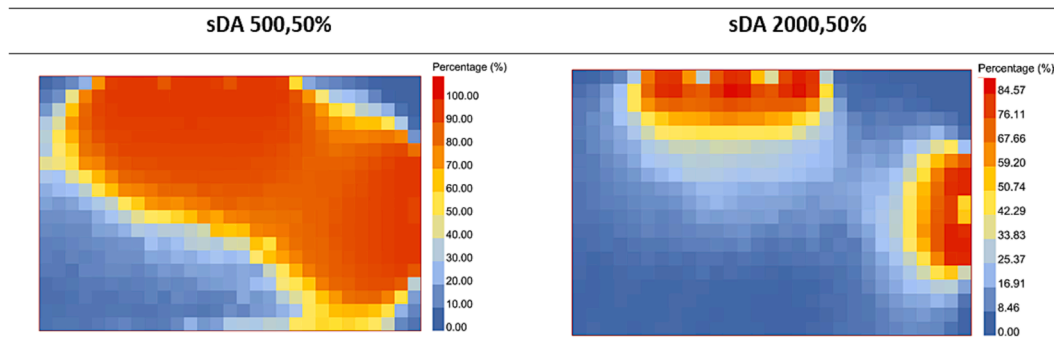
A-si thin-film pv glass optical specifications.

Thickness configuration	Visible Transmittance (%)	G-value (%)	U-value (W/m ² K)	External light reflection (%)	Peak power (Wp/m ²)	Nominal peak power (W _p)	Length, width, thickness (mm)	Surface area (m ²)
6 T + 3.2 + 6 T/ 12Air/6T Low-E	30	7	1.6	7.3	28	20	1200,600,8.10 (EVA) 8.72 (PVB)	0.72

Table 8

A-si thin-film pv glass electrical specifications.

Thickness configuration	Visible Transmittance (%)	Open circuit voltage (V)	Short-circuit current (A)	Voltage at nominal power (V)	Current at nominal power (A)	Temperature coefficient of P _{mpp} (%/C)	Temperature coefficient of V _{oc} (%/C)
6 T + 3.2 + 6 T/ 12Air/6T Low-E	30	47	0.74	32	0.63	−0.19	−0.28

**Fig. 6.** Illustration of window size change during the optimization process.**Fig. 7.** Annual daylight autonomy results of base case model according to the 500 lx and 2000 lx thresholds.

back parts of the room; thus, it should be optimized for better daylight performance. The implemented PV glass generated 108 kWh and 148.5 kWh annual AC power per window on the east and south, respectively. Solar cells have lower transmittance values than traditional windows. Thus, they caused an increase in the lighting loads of the case room due to the illuminance level difference when applied to the windows. Annual lighting load ranges between 2451 kWh and 3728 kWh for the case room. The simulation engine calculates the energy generation of PV glass seasonally and annually for a climate-based evaluation. PV glass generates 54 kWh, 140.8 kWh, 241.3 kWh, and 182 kWh of electrical energy for winter, spring, summer, and fall seasons. Some PV glass may store heat during the power conversion and increase indoor air temperatures. However, the implemented PV glass has Low-E coatings that act as a thermal insulation layer for the window. Thus, the simulation engine calculates the indoor air temperatures to evaluate the thermal performance of the case room. The average annual indoor temperatures are 22.3 °C and 26.6 °C for the PV glass and base case model.

3.3. PV glass optimization results

3.3.1. Pareto-front analysis: Optimum design variables and objectives

Octopus multi-objective optimization algorithm runs with the Grasshopper interface for one week. After computing, the algorithm stopped working, and the results were obtained on the three-dimensional axis. While evaluating the results, the optimum Pareto-front results with the highest sDA and the lowest thermal loads were selected. Pareto-front aims to improve both objectives in the optimization process. However, these objectives influence each other, meaning that as one of the objectives increases, the other may decrease due to the influence of one on another. Thus, a multi-objective evolutionary algorithm is significant in this sense. The optimization aims to increase sDA, reduce the total thermal loads of the building, and increase the energy-saving potential of the studio. The optimum Pareto solutions are selected according to the possible highest sDA and the lowest total heating and cooling load. Fig. 9 shows the multi-axe view of the evolutionary algorithm and selection of the Pareto-front genomes. The solutions with at least 50 % of sDA are indicated with a red line on the figure. The lowest total thermal load above this line corresponds to the Pareto-front

Table 9

Pareto-front optimization genomes show each objective and variable in detail.

Variables					Objectives					
Window surface (m ²)		Transmittance (%)	sDA (%)	(%) ¹	(%) ²	Heating load (kWh)	Cooling load (kWh)	Total thermal load (kWh)	(%) ³	(%) ⁴
East/South	Total									
Base Case										
12.6/8.4	21	75	59.9	–	–	7,909,507	1,114,731	9,024,238	–	–
30 % transmittance PV glass										
17.28/11.52	28.8	30	28.8	–31.1	–	7,910,341	1,097,786	9,008,127	0.17	–
Pareto-front genome (1)										
16.62/14.7	31.32	40	55.37	–4.53	26.6	8,117,258	1,131,037	9,248,295	–2.48	–2.66
Pareto-front genome (2)										
18.28/14.7	32.98	40	58.24	–1.66	29.4	8,151,201	1,136,220	9,287,421	–2.91	–3.10
Pareto-front genome (3)										
19.94/10.5	30.44	39	50	–9.9	21.2	8,101,755	1,127,855	9,229,610	–2.27	–2.45
Other Pareto solutions										
21.61/11.55	33.16	39	56	–3.9	27.2	8,156,232	1,136,444	9,292,676	–2.97	–3.15
23.27/10.5	33.77	37	54.43	–5.47	25.6	8,168,928	1,138,303	9,307,231	–3.13	–3.32
16.62/19.95	36.57	38	62.21	2.31	33.4	8,220,917	1,148,080	9,368,997	–3.82	–4.00
19.94/16.8	36.74	39	64	4.1	35.2	8,226,570	1,148,257	9,374,827	–3.88	–4.07
18.28/19.95	38.23	38	64.97	5.07	36.2	8,254,787	1,153,322	9,408,109	–4.25	–4.44
23.27/10.5	33.77	34	50.82	–9.08	22	8,168,928	1,138,303	9,307,231	–3.13	–3.32
23.27/12.6	35.87	38	59.5	–0.4	30.7	8,210,905	1,145,113	9,356,018	–3.67	–3.86
18.28/21	39.28	38	66.2	6.3	37.4	8,275,581	1,156,706	9,432,288	–4.52	–4.70
16.62/14.7	31.32	38	50.62	–9.28	21.8	8,152,827	1,112,472	9,265,299	–2.67	–2.85
16.62/16.8	33.42	34	50	–9.9	21.2	8,158,731	1,137,836	9,296,567	–3.01	–3.20
18.28/19.95	38.23	37	63.5	3.6	34.7	8,254,787	1,153,322	9,408,109	–4.25	–4.44
16.62/16.8	33.42	37	55.32	–4.58	26.5	8,213,723	1,142,837	9,356,560	–3.68	–3.86
26.59/10.5	37.09	40	63.35	3.45	34.6	8,236,553	1,148,734	9,385,287	–4.00	–4.18
16.62/19.95	36.57	38	62.72	2.82	33.9	8,220,917	1,148,080	9,368,997	–3.82	–4.00
21/18.28	39.28	37	65.15	5.25	36.4	8,275,581	1,156,706	9,432,287	–4.52	–4.70
16.62/19.95	36.57	34	57.7	–2.2	28.9	8,220,917	1,148,080	9,368,997	–3.82	–4.00
23.27/12.6	35.87	40	62.4	2.5	33.6	8,210,905	1,145,113	9,356,018	–3.67	–3.86
(%) ¹ : sDA difference between the base case and the Pareto-front gene										
(%) ² : sDA difference between the 30 % transmittance PV glass and the Pareto-front gene										
(%) ³ : Total heating and cooling load difference between the base case and the Pareto-front gene										
(%) ⁴ : Total heating and cooling load difference between the 30 % transmittance PV glass and the Pareto-front gene										
:: Pareto-front genomes										

(%)¹: sDA difference between the base case and the Pareto-front genome

(%)²: sDA difference between the 30 % transmittance PV glass and the Pareto-front genome

(%)³: Total heating and cooling load difference between the base case and the Pareto-front genome

(%)⁴: Total heating and cooling load difference between the 30 % transmittance PV glass and the Pareto-front genome

:: Pareto-front genomes

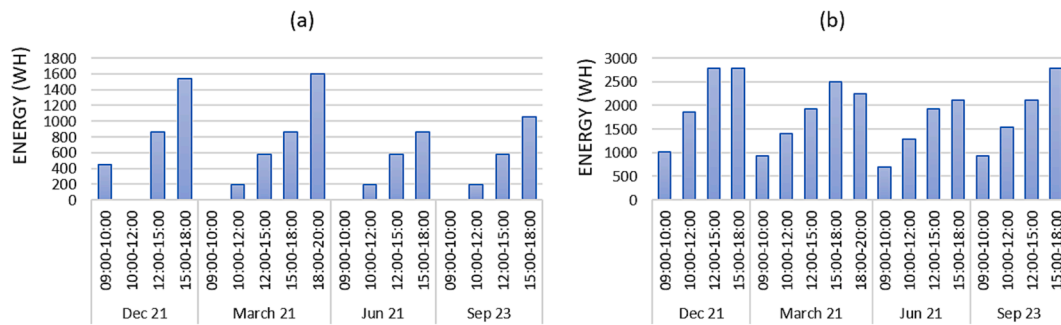


Fig. 8. (a) Daily energy consumption for lighting during the daytime in the clear sky with the sun (b) Daily energy consumption for lighting during the daytime in the overcast sky.

genomes for this optimization study.

Table 9 below shows the results in detail. The three best-performed solutions were selected as indicated with a grey color on the table. In one solution [i.e., *Pareto-front genome (1)*], sDA reached 58.24 % without falling below the threshold level with 40 % transmittance of the PV glass. In addition, the total thermal load of the studio increased by 2.91 % compared with the base case model.

The simulation engine calculates total heating and cooling loads as 8,151,201 kWh and 1,136,220 kWh, respectively. In this genome, the glass surface area is optimized as 14.7 m² for the South façade and 18.28 m² for the East façade. In total, the algorithm obtains 32.98 m² of glass surface area. It is increased by 49.1 % compared to the existing model.

Regarding the glaring risk of the studio, sDA is calculated as 58.24 %, 55.37 %, and 50 % for the three best-performed genomes, respectively. These are increased by 29.44 %, 26.57 %, and 21.2 % compared with the

30 % transmittance PV glass. sDA values are calculated very close to the base case situation, with less glare risk and more visual comfort for the occupants (Fig. 10). At least 2000 lx of illumination was found usable in 12.1 %, 9.9 %, and 11.25 % of the analysis area in half of the year for the three genomes.

Annual and seasonal lighting load and PV electrical energy generation of the selected Pareto-front genome are calculated to evaluate the energy performance of the optimized model. According to the results, the seasonal lighting energy consumption of optimized PV glass is calculated as 1153–1495 kWh, 1119–1440 kWh, 192–426 kWh, and 107–453 kWh for winter, spring, summer, and autumn periods for the two sky types respectively: clear sky with sun and overcast sky (Table 10). Table 9 shows the overall energy and daylighting data of the studio. Total power generation for a whole year is 375.15 kWh and 432.2 kWh for the south and east façades, respectively. Energy

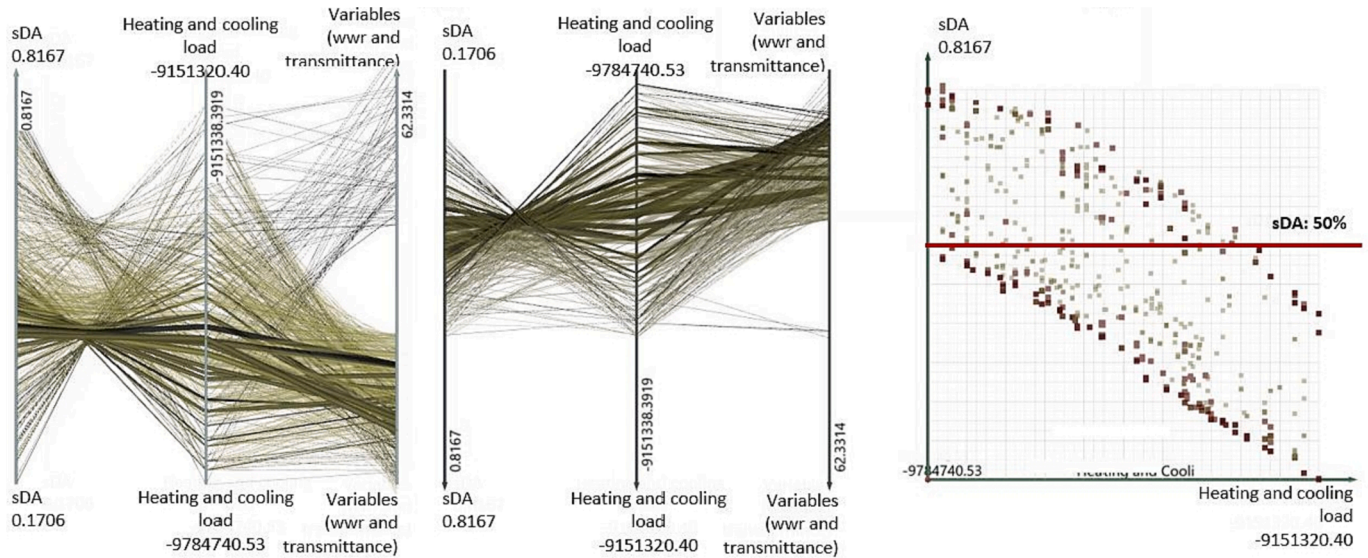


Fig. 9. (a) The multi-axe view of the evolutionary algorithm (b) Indication of the Pareto-front optimization results on the axis.

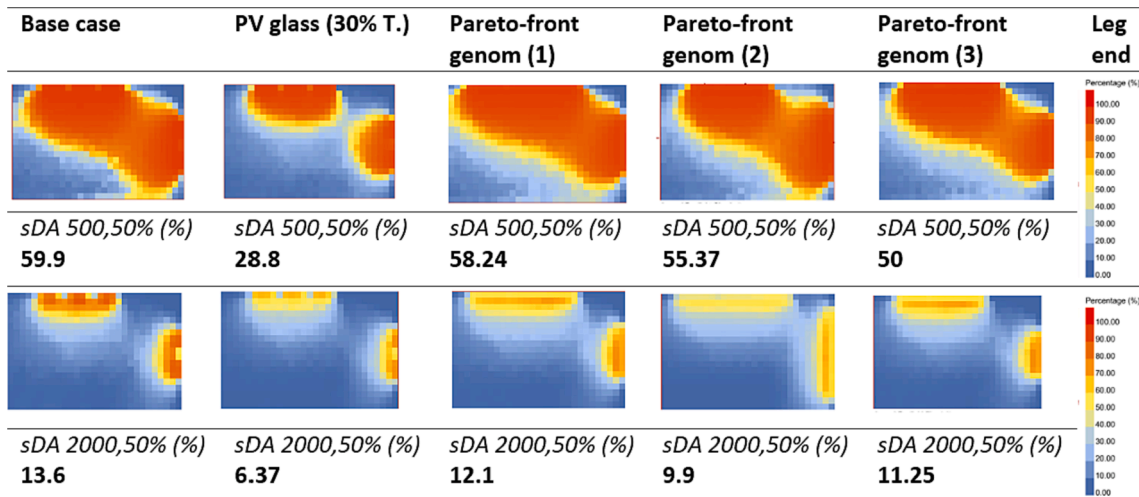


Fig. 10. The base case, 30% transmittance PV glass, and three best-performed Pareto-front genomes' daylight autonomy results according to the 500 lx and 2000 lx thresholds.

Table 10

Seasonal lighting load of the studio and PV glass electrical energy generation comparison.

Season	Data Input			PV electricity generation (kWh)		
	Lighting load range (kWh)					
	Base case	30 % transmittance PV glass	Pareto-front genome (1)	Base case	30 % transmittance PV glass	Pareto-front genome (1)
Winter	1178–1514	1392–1549	1153–1495	–	54	74.7
Spring	1067–1413	1322–1532	1119–1440	–	140.8	172.1
Summer	97–360	428–501	192–426	–	241.3	320.4
Fall	109–441	366–524	107–453	–	182	240.2
Total	2453–3730	3509–4106	2572–3815	–	620.9	807.35

generation is 807.35 kWh annually (Fig. 11). See (Table 11).

3.3.2. Optimum daylight performance model: Highest sDA solutions

The optimization goal is to achieve an sDA of at least and preferably higher than 50 %. The base-case results have shown that sDA was considerably reduced in low-transparency PV glasses due to the low transmittance of daylight to the studio. However, as the window size changed with the optimization, the highest sDA was achieved at 82 %,

with a 40 % transmittance of the PV glass (Table 12). In this genome, sDA increased by 22.1 % compared to the base case results and reached 82 %. Heating and cooling loads were increased by 8.23 % and 7.68 % compared to the base case, respectively, which was undesirable for the studio. Lastly, the window size has been expanded by 153.3 % and increased to 53.2 m². During the optimization process, the largest window size is 54.25 m², in which the sDA is calculated as 81.6 %, and total thermal loads are estimated as 9.784.740 kWh.

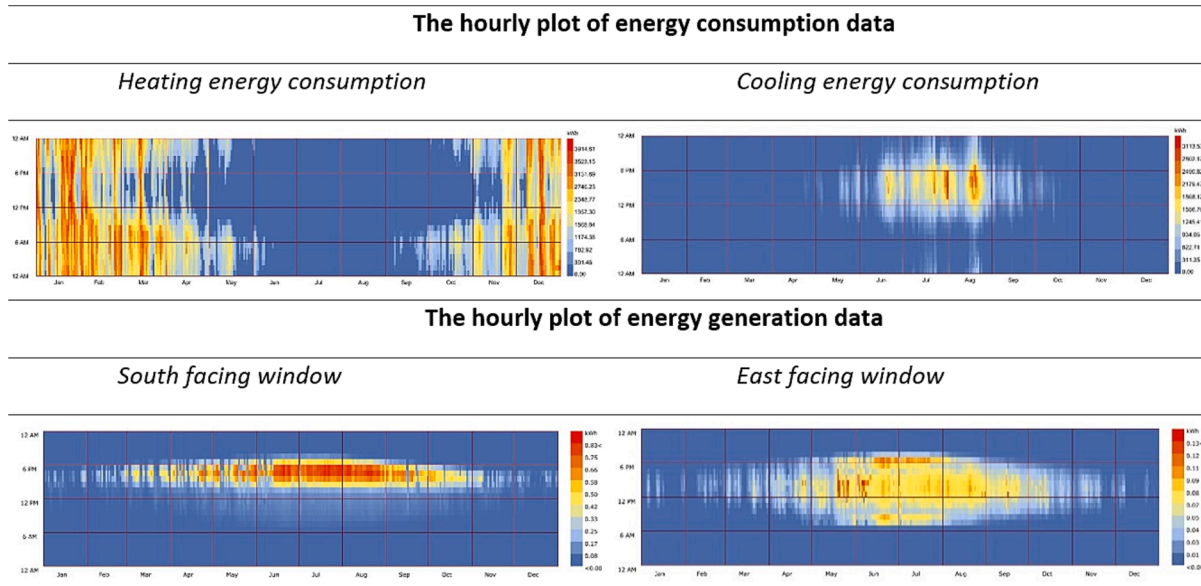


Fig. 11. The hourly plot of heating and cooling energy consumption data and PV electrical energy generation data of the Pareto-front (1) solution.

Table 11
Overall energy and daylighting data.

Energy Data	Data Input		
	Case model	30 % Transmittance PV glass	Pareto-front genome (1)
Annual energy consumption to heat the whole building (kWh/m ²)	12,554	12,556	12,884
Annual Energy consumption to cool the whole building (kWh/m ²)	1769	1742	1795
Heat gain from windows (kWh/m ²)	18,233	4677	7052
Infiltration heat gain (kWh/m ²)	522	522	780
Heat removal from windows (kWh/m ²)	4375	2492	3701
Heat removal from infiltration (kWh/m ²)	2383	2379	3544
Range of annual lighting load for the case room (kWh)	2453–3730	3509–4106	2572–3815
Annual PV energy generation (kWh)	–	620.9	807.35
The power output of facades (kWh)	–	East: 324 South: 297	East: 432.2 South: 375.15
sDA500,50 (%)	59.1	28.8	55.37

3.3.3. Optimum energy performance model: Lowest thermal load solutions

As a result of the entire optimization process, the lowest total thermal load has been achieved at 9.151.337 kWh, with a 39 % transmittance of PV glass and 27.12 m² surface area (Table 13). The annual total thermal load is increased by 1.58 % compared to the base case situation. The sDA is 44.4 % for this genome which is below the acceptable level. The simulation engine calculates annual heating and cooling loads as 8.033.983 kWh and 1.117.354 kWh, respectively. Both thermal loads are calculated as higher than the base case condition. Total thermal loads, heating, and cooling loads are increased by 1.40 %, 1.57 %, and 0.24 %, respectively, compared to the base case model. This genome optimized the glass surface area as 16.62 m² for the South façade and 10.5 m² for the East façade. The window size has been enlarged by 22.5 % and increased to 27.12 m². It is noted that the optimization algorithm tends to enlarge the window size to increase annual daylight autonomy, but this causes an increase in the total energy

consumed to heat and cool the building. During the optimization process, the narrowest window size is noted for this genome, in which the total thermal load is estimated as the lowest.

4. Conclusions

The study applies a multi-objective evolutionary optimization algorithm for a-Si PV glass' transmittance and window size to enhance the building's energy performance, the case room's daylight performance, and the PV's energy generation capacity. The following is a list of the key findings:

- The computational algorithm performed better in improving the studio's sDA rather than the building's thermal loads. The final sDA is significantly enhanced compared to the base case model and 30 % transmittance PV glass model. It is crucial to achieving such an increase in sDA in a scenario where the transparency is very low and close to the transmittance of a PV glass. In this respect, the sDA results exceeded the target value and were satisfactory. The key reason for achieving such high sDA may be due to optimizing only window-based parameters. It may also lead to low improvements in the thermal loads of the building because it depends on many variables instead of only window-based ones.
- Although the sDA of the optimized model and the base case model is quite close, the optimized model has improved daylight distribution and reduced glare risk. It shows the PV glass's capacity to improve daylight's homogenous distribution.
- The transmittance range of the glass during the optimization process is kept very close to the transmittance of the actual PV glass. This way, it aims to test the PV glass's sDA potential. During the optimization, enlarged windows were obtained to achieve high sDA. It has been observed that during the optimization, the window sizes are narrower in the Pareto-front results and the narrowest at low thermal loads. The optimization algorithm narrows the window sizes to reduce heat losses and infiltration. It reduces the heating load of the building in this way.
- Although the optimization algorithm increased the studio's potential in terms of sDA, the expected results could not be obtained for the thermal loads of the building. The optimization genome with the lowest thermal loads received a slight increase in total thermal loads compared to the current situation. It is because the sDA and thermal loads are inversely proportional. While the optimization algorithm

Table 12
Optimization genomes for the highest sDA showing each objective and variable in detail.

Variables						Objectives				
Window surface (m ²)		Transmittance (%)	sDA (%)	(%) ¹	(%) ²	Heating load (kWh)	Cooling load (kWh)	Total thermal load (kWh)	(%) ³	(%) ⁴
East/South	Total									
Base Case										
12.6/8.4	21	75	59.9	–	–	7,909,507	1,114,731	9,024,238	–	–
30 % transmittance PV glass										
17.28/11.52	28.8	30	28.8	–31.1	–	7,910,341	1,097,786	9,008,127	0.17	–
Other Pareto solutions										
33.24/20	53.2	40	82	22.1	53,2	8,560,372	1,200,359	9,760,731	–8.16	–8,35
33.25/21	54.25	39	81.6	21.7	52,8	8,580,953	1,203,787	9,784,740	–8.42	–8,62
33.24/19.95	53.19	40	81.6	21.7	52,8	8,560,372	1,200,359	9,760,731	–8.16	–8,35
33.24/19.95	53.19	40	81.1	21.2	52,3	8,560,372	1,200,359	9,760,731	–8.16	–8,35
31.58/21	52.58	39	80.5	20.6	51,7	8,547,007	1,198,539	9,745,546	–7.99	–8,18
31.58/21	52.58	39	79.8	19.9	51	8,547,007	1,198,539	9,745,546	–7.99	–8,18
29.9/21	50.92	39	79.1	19.2	50,3	8,513,096	1,193,343	9,706,439	–7.55	–7,75
28.25/18.9	47.15	40	78.2	18.3	49,4	8,437,607	1,181,248	9,618,855	–6.58	–6,77
31.58/21	52.58	37	78.9	19	50,1	8,537,007	1,198,539	9,735,546	–7.88	–8,07
29.9/21	50.92	37	77.6	17.7	48,8	8,513,096	1,193,343	9,706,439	–7.55	–7,75

Table 13
Optimization genomes for the lowest total thermal loads showing each objective and variable in detail.

Variables					Objectives					
Window surface (m ²)		Transmittance (%)	sDA (%)	(%) ¹	(%) ²	Heating load (kWh)	Cooling load (kWh)	Total thermal load (kWh)	(%) ³	(%) ⁴
East/South	Total									
Base Case										
12.6/8.4	21	75	59.9	–	–	7,909,507	1,114,731	9,024,238	–	–
30 % transmittance PV glass										
17.28/11.52	28.8	30	28.8	–31.1	–	7,910,341	1,097,786	9,008,127	0.17	–
Other Pareto solutions										
16.62/10.5	27.12	39	44.4	–15.5	15.6	8,033,983	1,117,354	9,151,337	–1.40	–1.78
16.62/11.55	28.17	24	23.59	–36.3	–5.21	8,054,735	1,120,744	9,175,479	–1.67	–2.09
16.62/11.55	28.17	30	32.8	–27.1	4	8,054,758	1,120,782	9,175,540	–1.67	–2.09
16.62/11.55	28.17	38	46.22	–13.7	17.4	8,054,835	1,120,744	9,175,579	–1.67	–2.09
16.62/10.5	27.12	37	41.36	–18.5	12.6	8,073,827	1,103,842	9,177,669	–1.70	–0.55
18.28/10.5	28.78	33	40.64	–19.3	11.8	8,067,845	1,122,581	9,190,426	–1.84	–2.25
18.28/11.55	29.83	27	31.7	–28.2	2.9	8,088,759	1,126,012	9,214,771	–2.11	–2.57
19.94/10.5	30.44	22	24.3	–35.6	–4.5	8,101,755	1,127,855	9,229,610	–2.27	–2.73
18.28/12.6	30.88	22	24.9	–35	–3.9	8,099,283	1,129,958	9,229,241	–2.27	–2.93
18.28/12.6	30.88	21	23.5	–36.4	–5.3	8,109,710	1,129,413	9,239,123	–2.38	–2.88

increases the sDA, it also aims to reduce the thermal loads. However, the numerical limitations in the variables were insufficient to reduce the thermal loads. Total energy consumption is slightly increased compared to the case where 30 % transmittance PV glass was implemented in the studio. This study does not aim to retrofit an existing building. Instead, it aims to understand the capacity of PV glazing using window-based variables. Thus, less improvement in energy performance has shown us the insufficient contribution and potential of PV glass in such a building.

- Since the optimization algorithm aims to increase sDA, it tends to expand the window sizes. Thus, seasonal and annual lighting loads are considerably reduced compared to the 30 % transmittance PV glass-integrated model before the optimization. The lighting loads are calculated very closely compared with the base case model. Window transmittance was 75 % in the base case model and 40 % in the optimized PV glass model. Although the transparency is considerably reduced, the lighting loads are almost identical. It is due to the expanding window sizes by the multi-objective evolutionary optimization algorithm.
- It is seen that the optimized PV glass generates 23.2 % more annual electrical energy than the non-optimized PV glass. The importance of window sizes and transparency was seen in this respect. Annual electricity generation on the East and South facades increased by 25 % and 20.8 %, respectively.

- The number of hours the user is uncomfortable during the year increased by 17 % and decreased by 36 % when the optimized PV glass is compared to non-optimized PV glass and the base case model.
- Infiltration heat removal is significantly increased compared to the base case model and non-optimized PV glass due to the enlarged window sizes. High infiltration heat removal may be one reason for not reducing heating loads during the optimization.

The items listed below may be important to guide researchers working in the field of performance and optimization of PV glass:

- Window-based parameters (i.e., window-to-wall ratio and window transmittance) are extremely effective in improving the daylight performance of a PV glass. Using these variables in optimization studies can improve the daylight performance of these buildings in such climates.
- In such a building and climate, it is necessary to increase the number of optimization variables to improve the energy performance of buildings where PV glass is implemented. Building envelope parameters (i.e., thermal transmittance of the wall, roof, floor, use of shading elements, natural ventilation, etc.) should also be included in the optimization algorithm because it is seen that window-based variables are not sufficient to reduce energy consumption from heating and cooling.

- In a Mediterranean climate, PV glass optimization is beneficial to reduce glare risks and enhance occupant visual comfort. To optimize this technology in low-latitude regions with high solar radiation can improve the daylight performance of buildings as well as the comfort of the users. In addition, since Low-E PV glass can reduce building cooling loads, it is strongly recommended to use it in regions with high solar exposure.

This study demonstrates the significant potential of PV glass to lower cooling loads and glare problems while enhancing occupant thermal comfort. Optimizing its architectural properties reveals its potential in terms of daylight performance, lighting energy consumption, and energy generation potential.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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