

APPLICATION OF ADVANCED COMPUTATIONAL BUILDING PERFORMANCE ANALYSIS TOOLS IN THE ARCHITECTURAL DESIGN OF NET-ZERO ENERGY BUILDINGS – CASE STUDY.

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Abstract

Architects worldwide have been tasked with the ambitious goal of designing net-zero energy buildings. This endeavour represents one of the most significant actions in the fight against climate change. Computer-based building performance analysis tools are poised to play a pivotal role in this new approach to architectural design. This article aims to explore the process of architectural design for net-zero energy buildings (NZEBS) through the application of the latest computer-based building performance analysis tools. The research seeks to demonstrate how and at which stages of architectural design these advanced simulation programs and databases on the energy efficiency of completed buildings are employed. The foundation of this research lies in the integration of cutting-edge science, technology, and analytical methods to design buildings with minimal energy consumption and reduced greenhouse gas emissions. A case study methodology was employed to investigate these issues. The findings of the research indicate that these tools empower architects to perform crucial analyses throughout the design process, facilitating the creation of net-zero energy buildings.

Keywords: Computer simulation-based Building Performance Analyses (BPA); Computer simulation tools in architectural design; Designing net zero energy buildings; Daylighting strategies; Visual comfort, High-performance office buildings.

1. INTRODUCTION

The European Parliament has adopted a revised version of the Energy Performance of Buildings Directive (EPBD). Among its provisions, the directive stipulates that all new buildings must achieve zero on-site emissions from fossil fuels, with publicly owned buildings required to meet this standard by 2028 and all other new buildings by 2030. In this context, the capacity to design net-zero energy buildings has assumed a new level of importance. It is now a critical aspect of architectural design practice, with a clearly defined deadline for implementation.

This raises the question of whether the architectural community is fully prepared to face this challenge. Although the issue is undeniably complex, this article

does not aim to provide a comprehensive discussion of the problem. Instead, the focus is on presenting the process of designing net-zero energy buildings (NZEBS) using the latest computer-based building performance analysis tools. The objective of this research is to explore how and at which stages of architectural design these advanced simulation programs and energy efficiency databases for completed buildings are used.

The MIT Department of Architecture offers a course entitled Sustainable Building Design, which equips students with the knowledge to apply the latest scientific, technological, and analytical techniques in designing buildings with minimal energy consumption and greenhouse gas emissions. This course is led by Professor Christoph Reinhart, who is also the co-founder of

Solemma, a spinoff from Harvard University. This connection is particularly relevant as Solemma is the developer of Climate Studio [1], described as “the fastest and most accurate environmental performance analysis software for architecture”.

The foundation of this research lies in the application of these advanced technologies and analytical methods within the architectural design process. The focus of the architectural project is the conceptual design of an office building, and a case study approach was adopted as the primary research method. The following computational tools were used in the study: Climate Studio (incorporating Radiance, Daysim, Evalglare, EnergyPlus, and Archsim), Autodesk Ecotect, Climate Consultant, Climaplus, Autodesk FormIt, and Dynamic Overshadowing.

2. STATE OF THE ART

Researchers have been analysing building performance for more than 50 years [2, 3, 4, 5]. The impact of architectural decisions on building performance has been considered theoretically since the 1990s ([6, 7, 8, 9, 10]). In contrast, research on “architect-friendly” Building Performance Analysis (BPA) computer simulation tools has been conducted for approximately 40 years. The first computer programs developed for architects include Climate Consultant [11, 12, 13], Radiance [14, 15], and Ecotect [16, 17, 18].

A critical mass was reached in the early 21st century due to the increasing need to create high-performing buildings alongside advancements in computer software. The current state of the art is most influenced by research conducted by Marilyne Andersen [19], John Mardaljevic [20], and Christoph Reinhart [21], along with their colleagues. The first software enabling comprehensive BPA emerged around 2012, including DIVA, the Autodesk Revit analysis tools, and Ladybug Tools. The first monographs describing these new computer-based methods, techniques, and tools in architectural design were published in 2014 [22, 23].

Leading centres for the development of these technologies are architectural institutions such as the MIT School of Architecture and Planning (Sustainable Design Lab [24]), the School of Architecture, Civil and Environmental Engineering (ENAC) at École Polytechnique Fédérale de Lausanne (EPFL) (Laboratory of Integrated Performance in Design [25]), and the School of Architecture, Building and Civil Engineering at

Loughborough University. Numerous PhD theses from these research centres are available [26, 27, 28, 29, 30, 31, 32, 33]. The latest capabilities of computer-based tools are presented through regularly updated video tutorials on Solemma’s website [1].

Recent research demonstrates the potential for applying the methods and techniques discussed in this article at an urban scale through the automation of analytical processes [30, 34, 35, 36]. The UBEM.IO tool [37] has been developed for this purpose. Additionally, ongoing research aims to develop a publicly accessible web-based tool for analysing the impact of design solutions on energy consumption and greenhouse gas emissions at the early stages of architectural design [31, 38, 39]. A Beta version of the ClimaPlus tool has been created [40].

3. METHODOLOGY

This article describes a comprehensive process to analyse architectural solutions in relation to indoor environmental quality, energy consumption, and greenhouse gas emissions. This method is used in the architectural design of NZEBs.

Analyses were conducted using Climate Studio, recognised as one of the most advanced, fastest and accurate computational tools available to architects. Additional simulation software was used at specific stages of the process, including Climate Consultant [13], Climaplus [40], Ecotect SolarTool [16, 17, 18], and Dynamic Overshadowing [41].

The process begins with an analysis of the climatic conditions. Subsequently, the building massing and façade solutions are evaluated to ensure optimal natural lighting, adequate sun protection, and visual comfort. The research process concludes with an examination of the energy consumption of the building during its operational phase, as well as an assessment of the electricity generated by the proposed photovoltaic panels.

The architectural project focuses on the conceptual design of an office start-up space located in Phoenix, Arizona. The underlying design philosophy is grounded in three core principles: high performance, flexibility, and high quality workspace.

High performance: In contemporary practice, a primary objective for architects should be the design of net zero energy buildings that are high performing. These buildings should minimise energy use through passive architectural solutions, be cost-effective to operate and offer ease of modernisation.

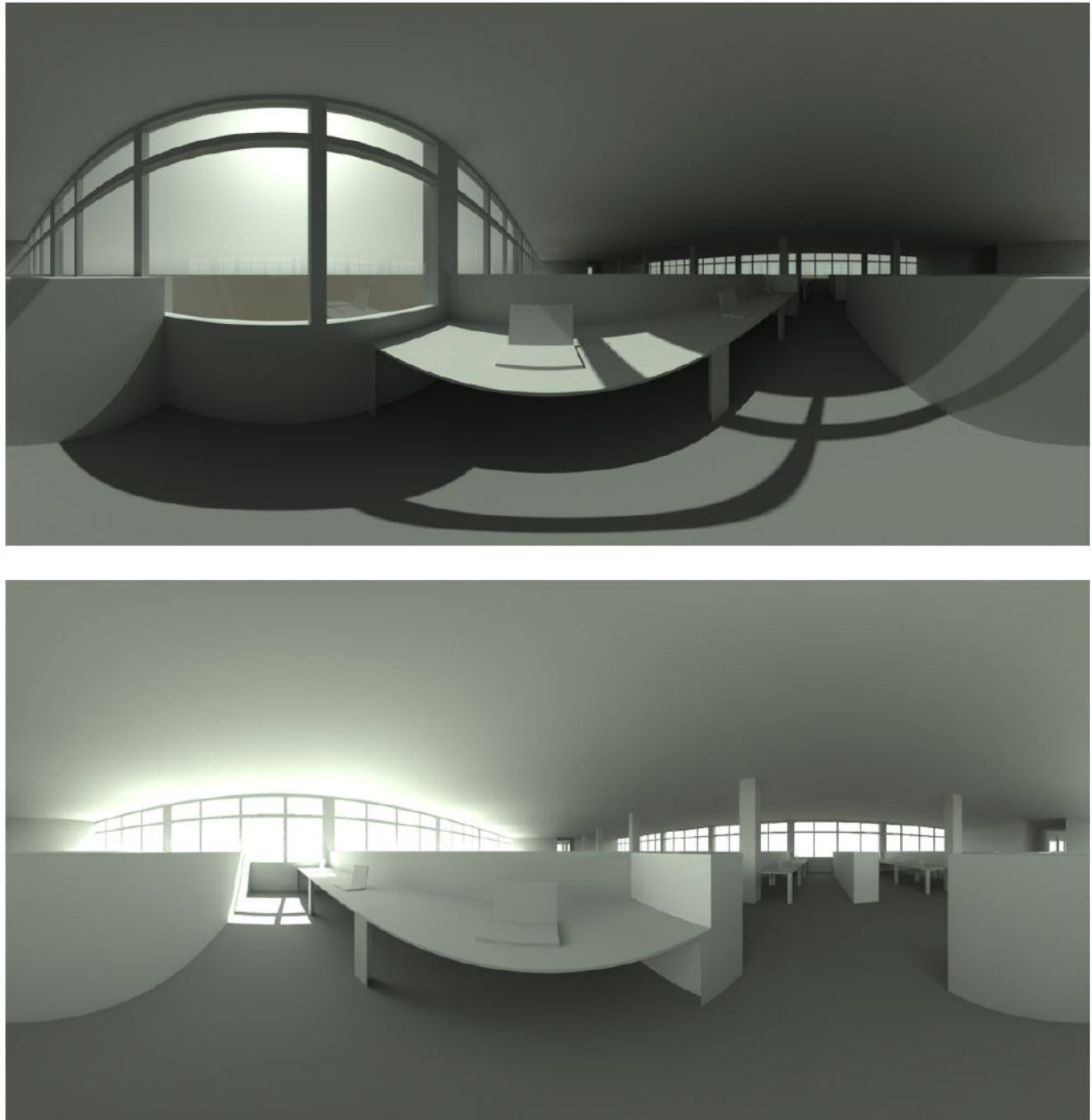


Figure 1.
Reversible office design for analysis, author: D. Masly

Flexibility: Functional flexibility in office buildings allows for varied usage and accommodates a variety of programmes. A flexible office can adapt quickly to changes in function, aligning with the critical sustainable design goal of maximising the useful life of a building. The concept of the reversible office was identified as an optimal solution. This approach accommodates all office typologies: cellular, combi, team, and open-plan. The hallmark of the reversible office is its asymmetrical structural layout (9m; 6m).

The spacing of the vertical window mullions aligns with the most commonly designed combi-office width, comprising two windows, each 1.35m wide. This configuration is equally suitable for open-plan office layouts. Figure 1 illustrates an open-plan team office arrangement, with desks perpendicular to the façade. Three rows of tables near each façade are adequately illuminated with natural light. Additionally, employees benefit from unobstructed views and operable windows.

High quality of workspace: During the lifecycle of an office building, total employee salaries are approximately 100 times higher than combined operating costs (energy, maintenance, and taxes), capital costs, and rental expenses. Consequently, the indoor environment of the office must be of the highest standard to maximise user productivity and efficiency. For this reason, the proposed office design is daylight-optimised, hybrid-ventilated and provides users with comprehensive control over indoor environmental conditions.

The objective was to analyse a building that exemplifies the fundamental principles of high-performance architectural design. To achieve this, the building was oriented along the east-west axis, resulting in two primary façades: the south and the north. The building is designed with a narrow floor plan (15m wide) to maximise daylight penetration and accommodate hybrid ventilation systems. The office building is approximately 77 metres in length, 9.6 metres in height (comprising two floors), and has a total area of approximately 2,300 m². The simulated office space is situated on the ground floor. A suspended ceiling is positioned at a height of 3.0 metres, with a floor-to-floor height of 4.2 metres. Each office storey is glazed from table height up to the suspended ceiling. The façade has a glass-to-wall area ratio of 60%. Glass with a visible transmittance (T_{vis}) of 0.51 – indicating the percentage of visible solar radiation transmitted through the glass – is utilised. A sidelighting system is incorporated, comprising a classic light shelf (1.2-metre internal shelf, 1.2-metre deep external sunshade, positioned at a height of 2.3 metres) and a fixed horizontal shading element (1.2-metre deep external sunshade, positioned at a height of 1.55 metres).

On the south-facing façade, oriented towards the equator, fixed horizontal sunshades were incorporated. These elements were chosen for their simplicity of maintenance, durability, and effectiveness in mitigating solar heat gain. On the north-facing façade, diffused daylight naturally illuminates the office spaces, typically eliminating the need for sunshades at this elevation.

Before analysing the impact of architectural design solutions on energy consumption, and, by extension, on greenhouse gas emissions, it is essential to refer to the most up-to-date energy consumption standards. These standards are derived from comparisons of buildings with similar functions constructed under specific climatic conditions. Such databases have been developed over many years. The MIT Sustainable Building Design course introduces two

notable examples: the Building Performance Database [42] and the Energy Star Portfolio Manager Target Finder [43]. It is reasonable to assume that similar resources are available to architects in many European Union countries; however, this topic falls outside the scope of this paper.

The chosen site is located in Phoenix, Arizona, within the Roosevelt Business Park Area. This location was selected to facilitate analyses in an extreme climate, specifically a hot, dry environment. Phoenix serves as a model location for this climatic category in the United States. Factors that support site selection include the presence of similar land uses in the vicinity, appropriate urban density characterised by low-rise neighbouring buildings, proximity to residential areas (potential sources of employees), and access to a nearby expressway.

The target Energy Use Intensity (EUI) for the project is less than 100 kWh/m². For comparison, the Energy Star 75 design targets are:

- Site EUI: 42 kBtu/ft² (132 kWh/m²)
- Source EUI: 98.3 kBtu/ft² (310 kWh/m²).

These benchmarks were obtained using the Energy Star Portfolio Manager Target Finder [43]. Furthermore, the Building Performance Database [42] provided comparable EUI values for the specified climatic conditions.

4. RESULTS

The research project employed the following analytical techniques:

- Climate analysis
- Evaluation of sun protection effectiveness
- Illuminance level analyses
- Visual comfort assessments using the Daylight Glare Probability (DGP) method
- Analysis of energy consumption during building operation, including heating, cooling, and lighting
- Assessment of the generation of electricity from photovoltaic panels installed on the roof of the designed building.

4.1. Climate Analysis – Passive Design Strategies

Phoenix has a BWh classification under the Köppen system, indicating a subtropical hot desert climate with winter temperatures dropping to 2°C and summer temperatures reaching up to 44°C. Under the ASHRAE climate zone classification, it is categorised as 1B – very hot-dry, while Victor Olgyay [44] classifies it as a hot-arid climate.

The following analyses were performed using the Climaplust program [40].

The diagram of monthly radiation levels (Fig. 2) for various surface orientations demonstrates that, from an energy perspective, the site presents an optimal architectural situation. Its alignment with the cardinal directions significantly reduces the building's energy consumption. During the summer, the southern and northern façades receive the least solar radiation, indicating that the building should be oriented along the east-west axis. This arrangement allows for the incorporation of effective fixed sunshades on the southern façade.

The degree days graph highlights the need for year-round passive cooling of the building. As a result, energy-efficient cooling systems will need to be considered for office spaces.

The psychrometric chart was generated using Climate Consultant [13]. It shows the percentage of occupied hours during which the indoor environment is comfortable without any design strategies: Phoenix – 19.5% (1,707 hours). The chart also highlights the most effective passive design strategies for the region, as follows:

- Internal Heat Gain – 25.5% (2,238 hours)

- Two-Stage Evaporative Cooling – 25.3% (2,217 hours)
- Sun Shading of Windows – 22.6% (1,976 hours)
- Passive Solar Direct Gain with High Mass – 18.2% (1,594 hours).

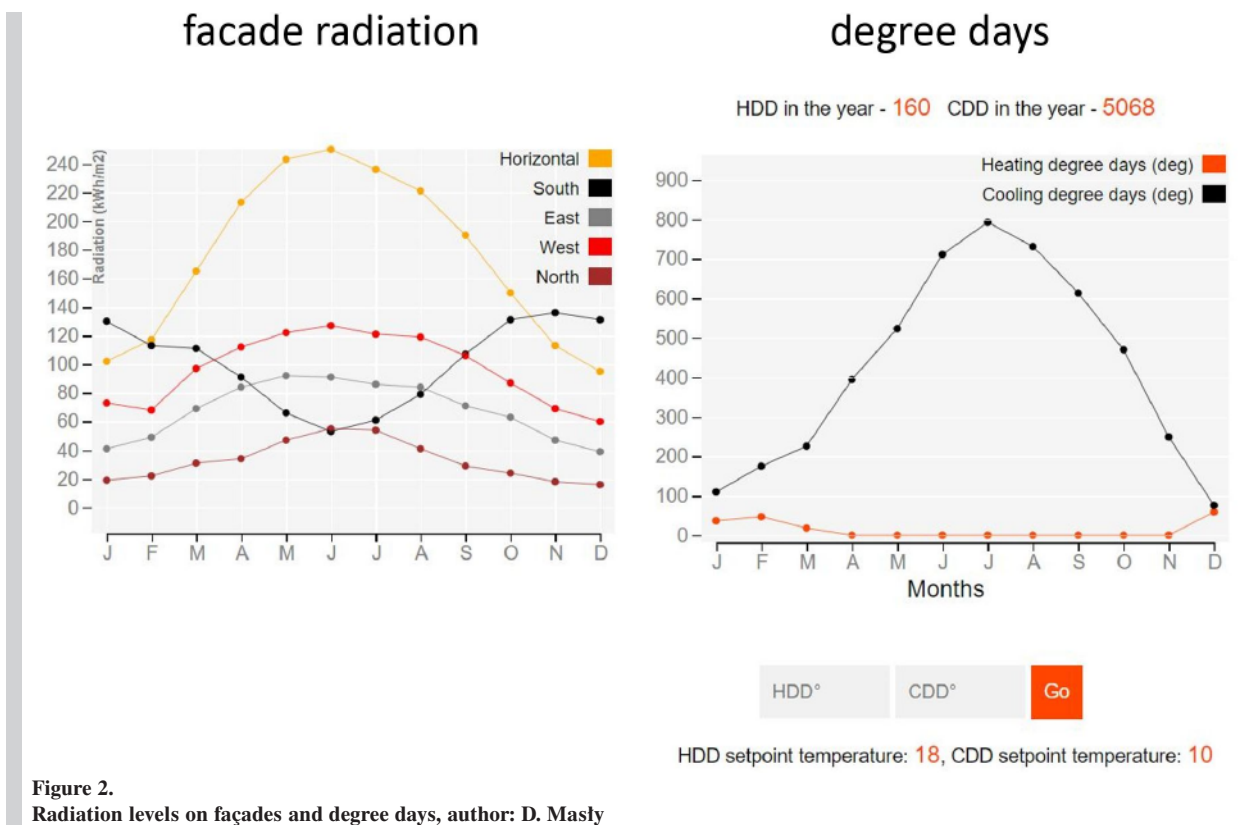
Given these results, Phoenix buildings should be designed to minimise direct solar gains.

4.2. Shading Study and Illuminance from Daylighting

Initially, analyses were conducted to assess the impact of building massing on illuminance levels from daylighting (daylight availability). Three massing models were selected for this analysis: a 1-storey deep open-plan office, a 1-storey reversible office, and a 2-storey reversible office.

1-Storey Deep Open-Plan Office

The office has dimensions of 50 x 50 m, which is a typical configuration for a deep open-plan office. The depth of the work zone extends approximately 20 m from the façade, with a central core located in the middle of the floor plan.



Daylight Availability: floor plans

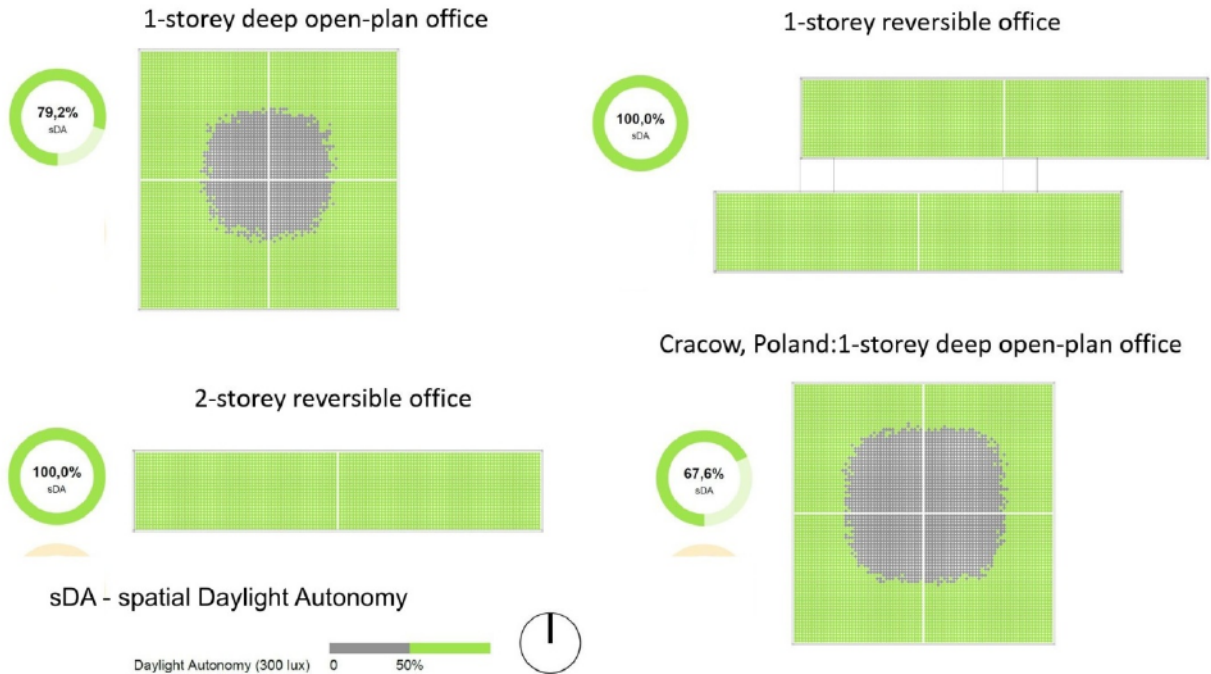


Figure 3.
Daylight availability in office models, author: D. Masły

2-Storey Reversible Office

The 2-storey reversible office is designed to be daylit and hybrid-ventilated. The depth of the work zone is approximately 6 m from the façade. Two cores provide access to four self-contained units (design modules), each covering an area of 240 m². This layout accommodates all types of office configurations: cellular, combi, open-plan, and team.

1-Storey Reversible Office

The 1-storey reversible office design consists of two workspaces, each comprising four design modules. These modules are spaced apart to create an atrium, with the two blocks connected at the locations of the technical cores.

Daylight availability is measured using spatial Daylight Autonomy (sDA 300, 50%) [22, 23, 45, 46]. For preliminary analyses, simplified models were constructed. The room height is 3 m, with the window sill at a height of 80 cm and the upper edge of the window at 3 m. Window frames were not included in the model. For a hot-dry climate, windows with the lowest U-value of 0.87 W/(m²·K) and a Solar Heat Gain Coefficient (SHGC) of 0.215 were selected.

The results are shown in Fig. 3. In the plan for the 1-storey deep open-plan office, the daylight zone

extends to a depth of 13 m. To enable comparison, a control simulation was conducted for Krakow, Poland, to assess the impact of a higher latitude – and consequently reduced annual daylight – on daylighting in office spaces. In this case, the daylight zone extends to 8 m on the north elevation. Based on the principle that daylight penetrates to a depth roughly twice the height of the window's upper edge, the expected result should be around 6 m. It is possible that the discrepancy is due to the simplified nature of the model.

For further simulation studies, the 2-storey reversible office model was selected.

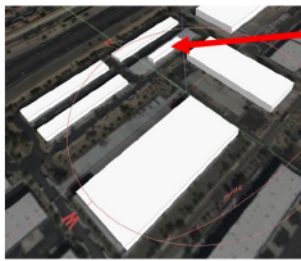
The climate analysis indicated that the building would require passive cooling throughout the year.

To design effective sun protection, it is essential to analyse the shading effects from surrounding objects, as well as the effectiveness of the proposed façade systems. Passive cooling is primarily influenced by external shading devices, but also by factors such as window openings (size, position, and orientation to the cardinal directions) and the type of glazing used.

When analysing the shading effects of neighbouring buildings, creating a 3D model of part of the city can be a challenging task. However, modern tools integrated into computer programs can greatly assist in

Site Analysis: Shading Study

Autodesk FormIt



Google Maps

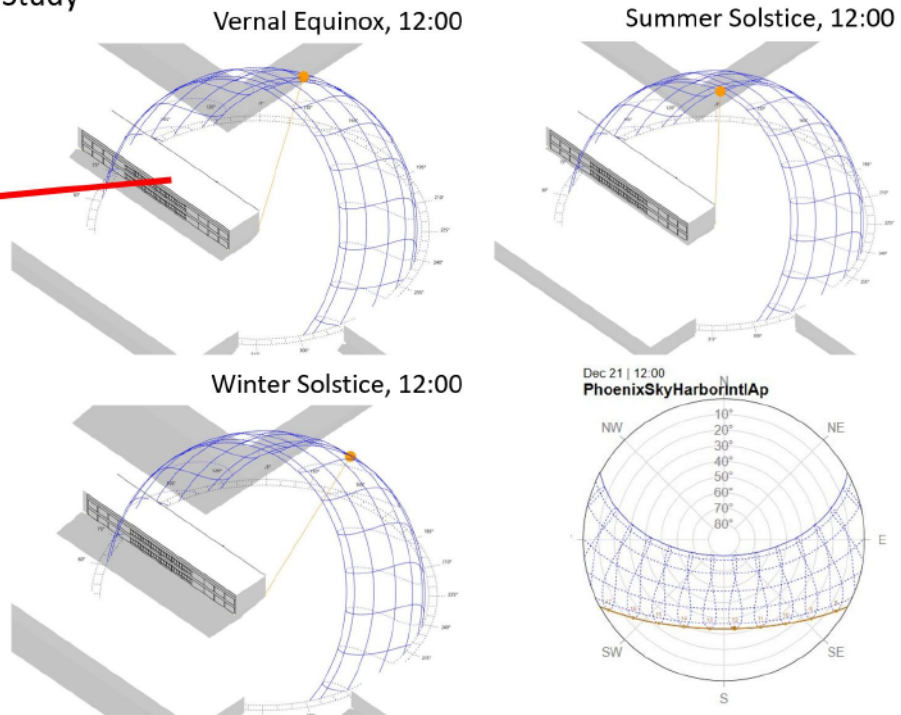


Figure 4.
Site analysis: Shading study results, author: D. Masly

this process. For example, the “3D Context Creator” tool in Autodesk FormIt automatically loads a Google map of the selected location. This tool generates 3D shapes of existing buildings, which can then be adjusted for height. The model is subsequently imported into Climate Studio, where shading analyses are performed.

The shadow analysis results show that the surrounding buildings are low enough that the designed building will only experience shading in winter, specifically just after sunrise (December 21 before 9:00 a.m.) and just before sunset (December 21 after 5:00 p.m.) (see Fig. 4).

The climate analysis indicated that the building would require passive cooling year-round (see “4.1. Climate Analysis (...)). Therefore, the next step was to design an effective sun protection system for the entire year. Fixed sunshades were chosen, as they are more durable, cost-effective and require less maintenance compared to movable ones. The building's location at this latitude ensures abundant daylight, further supporting this decision.

The building is oriented along the east-west axis, so only the sun protection for the south elevation was analysed. Analyses were conducted using the Ecotect Solar Tool program.

The 55 cm deep fixed sunshades effectively protect the windows on the south elevation from the spring equinox to the autumn equinox. However, given that Phoenix requires passive cooling throughout the year, additional analyses were conducted to assess the impact of sunshade depth on shading efficiency during specific times of the year. Based on these results, a depth of 120 cm was selected for the sunshades (see Fig. 5).

The east and west elevations feature only a few small windows to provide visual connections to the outside. These windows are equipped with movable Venetian blinds for additional solar control.

The following analyses focus on the impact of the designed façade system on daylight availability. Simulations were performed using Climate Studio, employing spatial Daylight Autonomy (sDA), which is currently the most widely used dynamic performance metric. The minimum lighting threshold was set at 300 lx and the sensor grid resolution was 0.6 m x 0.6 m. The sensors were placed at a height of 0.76 m above the floor. The office space was considered occupied from 8:00 to 18:00, Monday through Sunday.

The reflectance values for the room surfaces were as follows: outside façade – 30%, outside ground – 10%,

Fixed Sunshades on the South Elevation

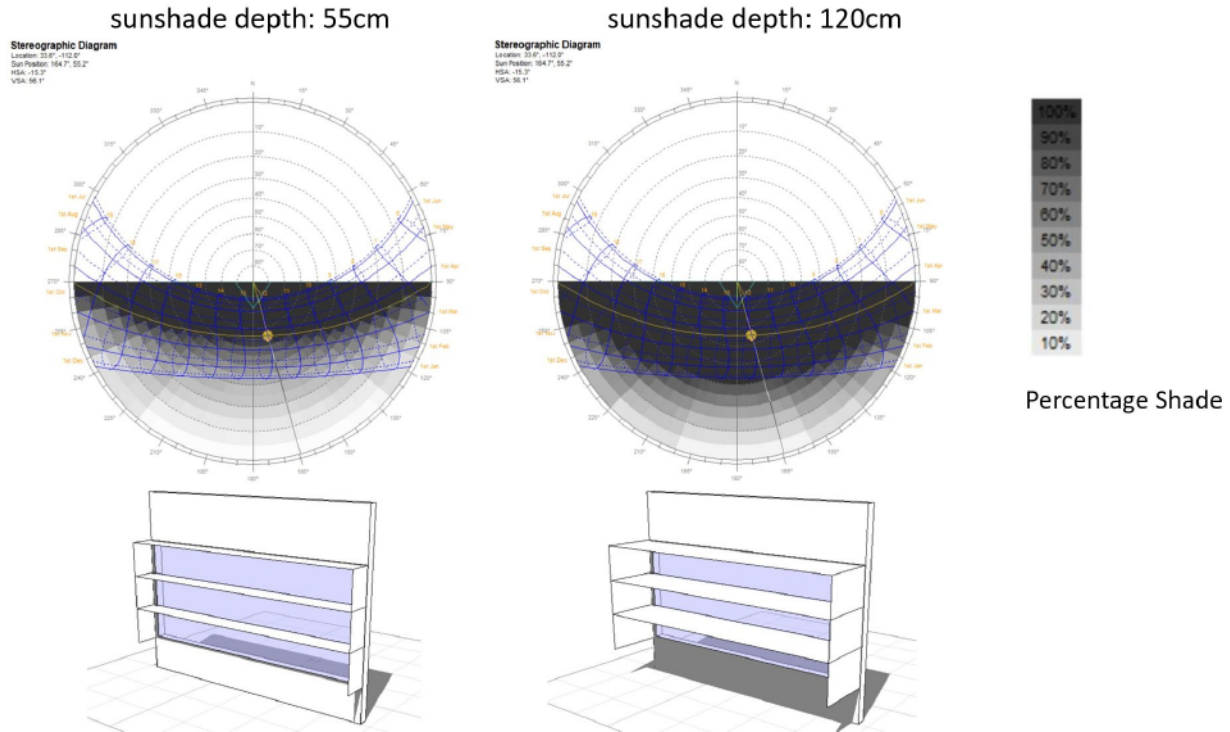


Figure 5.
Fixed sunshades on the south elevation for passive solar control, author: D. Masły

Daylight Availability: floor plan facade without shading system

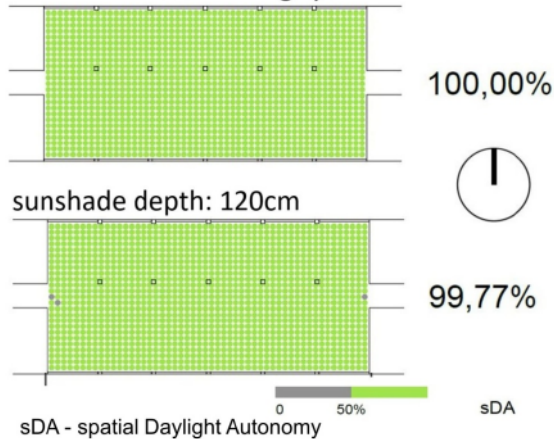


Figure 6.
Daylight availability: Spatial Daylight Autonomy (sDA) analysis, author: D. Masły

Visual comfort: floor plan facade without shading system

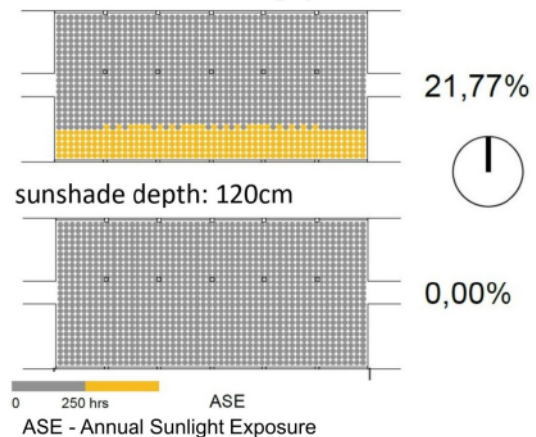


Figure 7.
Visual comfort: Annual Sunlight Exposure (ASE) analysis, author: D. Masły.

ceiling – 70%, floor – 20%, internal walls – 50%, frames – 50%, and the shading device/light shelf – 50%. The visual transmittance of the triple glazing was 51%.

The spatial daylight patterns throughout the year are

shown in Fig. 6. Two cases are presented: one without a shading system (sDA = 100%) and one with sunshades (sDA = 99.77%). The results demonstrate that the designed sun protection system ensures adequate daylight illuminance levels in the office space.

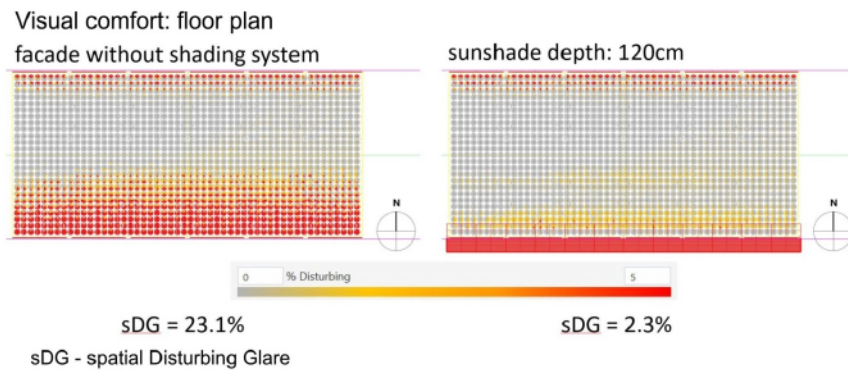


Figure 8.
Visual comfort: Daylight Glare Probability (DGP) analysis, author: D. Masly.

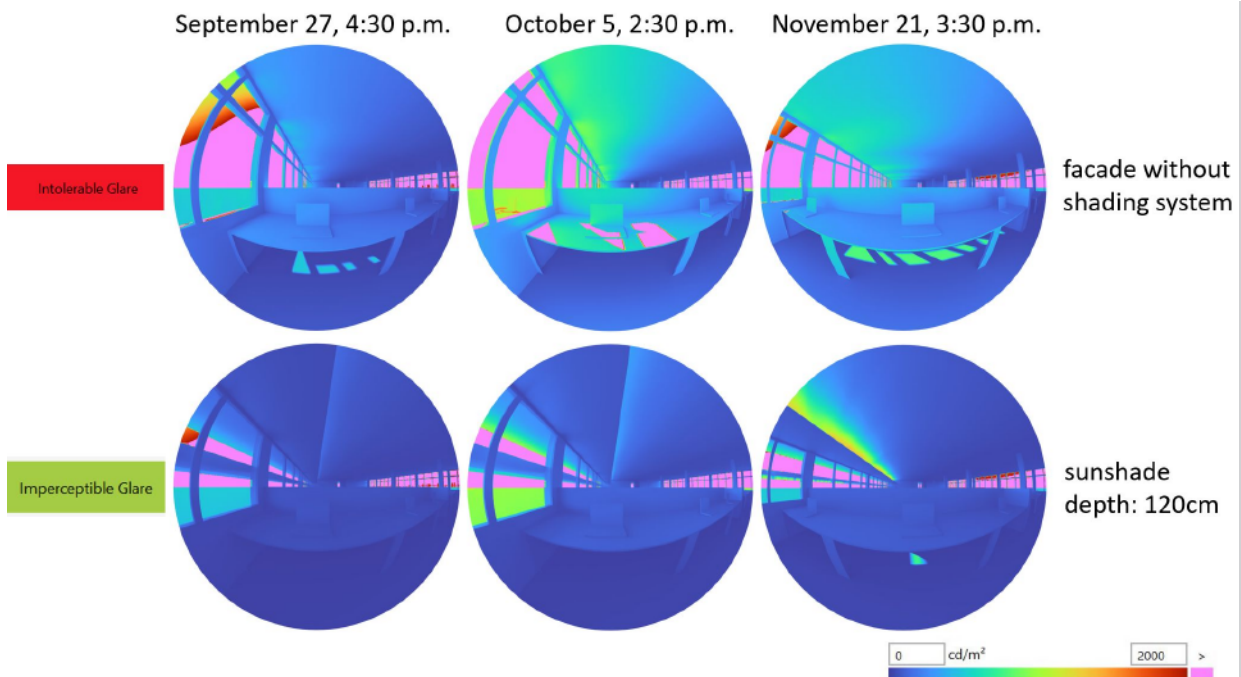


Figure 9.
Discomfort glare evaluation: Daylight Glare Probability (DGP) , author: D. Masly

4.3. Occupants' Visual Comfort

Two methods were used to analyse visual comfort: Annual Sunlight Exposure (ASE) [45] (Fig. 7) and Daylight Glare Probability (DGP) [47, 48] (Fig. 8). The ASE method is incorporated into the LEED green building rating system [49], while the DGP method is recommended by the European Daylighting Standard EN17037 [50].

The effectiveness of the designed shading system is clearly visible. The risk of discomfort, measured by the ASE metric, has been reduced to 0. The results of the daylight glare risk analysis using the DGP method show that the shading system has successfully reduced spatial Disturbing Glare (sDG) from 23.1% to 2.3%, a

highly positive result. Numerous red “pizzas” on the north side indicate that the use of vertical shades on the north elevation will further reduce sDG.

Three moments during the months of September, October, and November were selected when the risk of daylight glare was intolerable in a room exposed to intense, direct sunlight. Fisheye luminance graphs were rendered for these scenarios. Similar fisheye views were then created for the façade with the designed shading system. The fisheye luminance graphs clearly illustrate how the luminance distribution changes and how the areas with the highest luminance are mitigated by the proposed architectural solution (see Fig. 9).

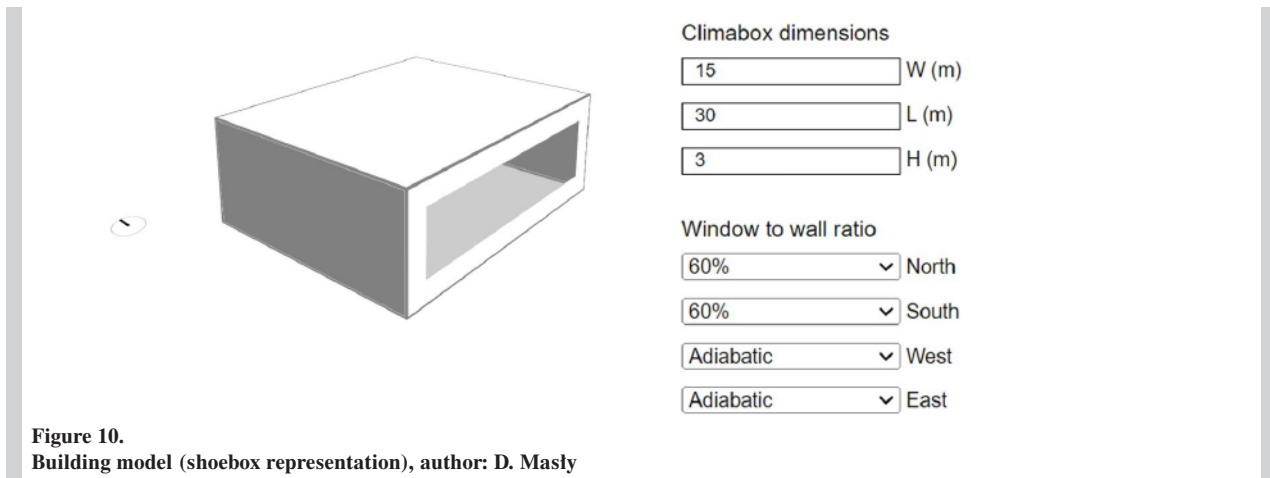


Figure 10.
Building model (shoebox representation), author: D. Masly

4.4. Energy Consumption

Energy consumption analyses were conducted using ClimaPlus, a software developed by members of the interdisciplinary MIT Sustainable Design Lab group, led by Prof. Reinhart. This “early-design web tool” [40] enables a rapid assessment of the impact of architectural design solutions (such as room depth, window size and placement, and orientation to cardinal directions), building envelope insulation, infiltration, HVAC systems, and electric lighting on energy consumption, CO_{2e} emissions, and costs.

For the analysis, the middle office space (located between the cores) on the ground floor was selected (see Fig. 10). All previous analyses were performed for this room. The built shoebox model corresponds to the room's dimensions, and the windows were set according to the design.

The “worst-case” options were selected, resulting in improved energy consumption performance (119 kWh/m²-yr) compared to the Energy Star 75 design target (Site – 42 kBtu/ft²-yr [132 kWh/m²-yr]) established at the outset. The EUI target remains below 100 kWh/m²-yr.

Upgrade 1 – Insulation of the Building Envelope and Building Infiltration

In the case of a narrow office building, insulating the external envelope is crucial to reducing energy consumption. A significant portion of the external wall is occupied by windows (WWR = 60%). The office building is located in a hot-dry climate, so, in addition to a low U-value (roof: 0.11 [W/(m²·K)]; wall: 0.13), windows with a low Solar Heat Gain Coefficient (SHGC) were selected. Double Low-E Low-Solar-Gain windows were chosen, with a U-value of 1.493

and an SHGC of 0.373. The designed building is highly airtight, with a measured air changes per hour (ACH) of 0.1. These improvements reduced the Energy Use Intensity (EUI) from 119 kWh/m²-yr to 85 kWh/m²-yr, representing a 30% reduction (see Fig. 11).

External sunshades were not included in the analysis performed using ClimaPlus. However, the designed sunshades would further reduce the energy consumption for cooling, thus contributing to a lower EUI. Additionally, the ClimaPlus program does not accommodate window selections required by Polish building technical standards. Had this functionality been available, the result would likely have been even more favourable. For the daylight analyses presented in this article, windows with the following parameters were selected: U-value of 0.87 and SHGC of 0.215.

Upgrade 2 – Energy-Efficient Lighting and Equipment

After optimising the building envelope insulation and airtightness, the next step is to select energy-efficient HVAC systems, lighting and equipment. The best solutions for this project include the following:

- Lighting (LPD – Lighting Power Density): 4 W/m², using LED lighting
- Equipment (EPD – Equipment Power Density): 6 W/m²

For comparison, typical LPD and EPD values are 10 W/m².

By choosing energy-efficient lighting and equipment, the Energy Use Intensity (EUI) improved from 85 kWh/m²-yr to 53 kWh/m²-yr, representing a 30% reduction compared to the initial result of 119 kWh/m²-yr (see Fig. 11). Furthermore, the

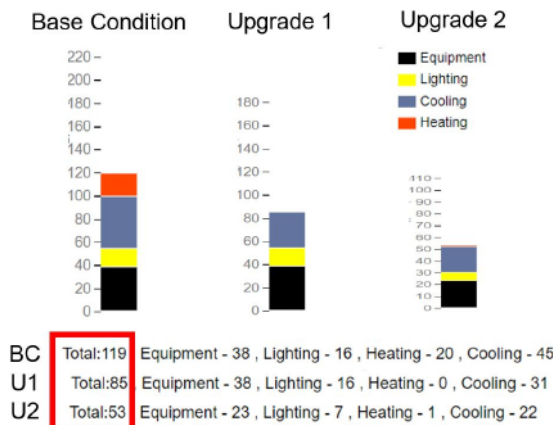
Energy Use Intensity in kWh/m².yr

Figure 11.

EUI study, author: D. Masły

selection of a heat pump for both heating and cooling further reduced energy consumption to 46 kWh/m².yr, marking a 6% improvement. Previously, the building was equipped with a gas-fired boiler for heating and direct expansion cooling.

PV System

The final task in the architectural design of a net-zero energy building is to analyse the potential for generating energy on the site to meet the EUI. Increasingly, architectural design software, such as Autodesk Revit, enables the modelling of photovoltaic panel surfaces and the simulation of the solar energy incident on them. For this study, the tool available within the Climate Studio program was used (Fig. 12a). Additional approximate data on annual solar radiation can also be obtained using the ClimaPlus program (Fig. 12b).

The photovoltaic system covers 70% of the roof area, equivalent to 816 m², and consists of 408 panels, each measuring 1 m x 2 m. Default settings were applied, including 18% panel efficiency and 96% inverter efficiency. The designed photovoltaic panels receive a radiation of 2060 kWh/m².yr, which results in an annual output of 290,470 kWh (2060 kWh/m².yr x 816 m² x 0.18 x 0.96 = 290,470 kWh). With an EUI of 53 kWh/m².yr, the building consumes 121,900 kWh per year (53 kWh/m².yr x 2300 m² (GFA) = 121,900 kWh). Thus, the building operates as a net energy-plus office.

Within the floor plan of the building, it would be feasible to design a 5-storey NZEB with a GFA of 5480 m².

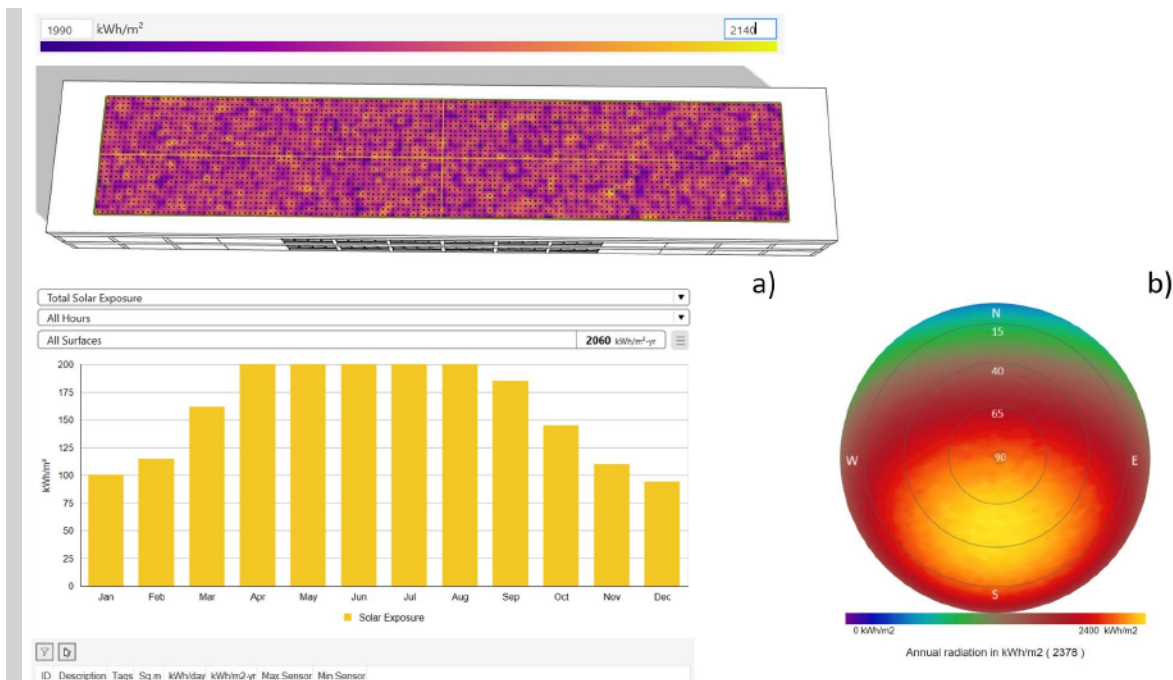


Figure 12.

Simulation of the photovoltaic system, author: D. Masły

5. DISCUSSION

Numerous architectural design handbooks emphasise the crucial role of architectural (passive) design solutions in determining building performance, particularly in terms of indoor environment quality (user comfort) and low energy consumption [22, 51]. Such solutions include the building's orientation to the cardinal directions, its massing, and façade design, including window placement and sunshading. These decisions should be made as early as possible, ideally during the architectural programming or conceptual design phase. These handbooks further assert that incorrect architectural (passive) decisions can rarely be remedied by even the most advanced technical or construction solutions.

Having conducted simulations for many years [52] [53], it has become increasingly evident that the introduction of high-quality thermal insulation materials, advanced windows, and high-performance HVAC systems, along with energy-efficient electric lighting (as mandated by EU regulations), has led to passive architectural design solutions having a relatively minor impact on reducing annual energy consumption (EUI). To test this hypothesis, a particularly pertinent case study was selected. The building is situated in a hot-dry climate at a low latitude. In this context, the building should be oriented along the east-west axis, with windows restricted to the south and north elevations, and properly applied solar protection to the south façade. The building depth should be kept small to ensure adequate daylight penetration.

The outcome of this design approach was highly satisfactory: it achieved optimal visual comfort while maintaining an impressively low energy consumption of 53 kWh/m².yr. For comparison, the renowned Bullitt Center, often cited as the benchmark for net-zero energy offices, achieves 50.5 kWh/m².yr, despite being located in a milder climate.

For provocation, several poor architectural decisions were intentionally made. The building now has two main elevations, east and west, with full glazing (80%) on both sides. In the Base Condition, energy consumption increased from 119 kWh/m².yr to 133 kWh/m².yr. Although this increase is notable, it highlights that architectural decisions are not as critical to energy reduction as commonly asserted. Next, another flawed decision was made by increasing the depth of the building from 15 to 30 metres, which required the workspaces to rely on electric lighting continuously. Subsequently, the energy consumption decreased to 123 kWh/m².yr.

After incorporating appropriate thermal insulation in

the building envelope, reducing the building's air infiltration, and improving the efficiency of electric lighting and equipment, the difference between the best and worst architectural solutions became almost negligible: 53 kWh/m².yr versus 52 kWh/m².yr. However, the less optimal design used marginally less energy.

The above analysis focused solely on annual energy consumption (EUI), which is, however, a flawed approach. Architectural design solutions, such as functional layout, building massing, room orientation, façade design, and the size and placement of windows and sunshades, are paramount not only in reducing energy consumption but also in ensuring thermal and visual comfort, as well as in reducing peak power demand. If these architectural decisions are made incorrectly and the functional layout proves unsuitable, it becomes nearly impossible to introduce energy-efficient heating and cooling systems, such as heat pumps. Consequently, achieving the primary goal of a zero-emission building becomes much more difficult and, in some cases, may be unachievable. The key takeaway is that close collaboration between professionals in the building sector is essential at every stage of the design process.

6. CONCLUSIONS

According to the EPBD directive adopted by the European Parliament, architects will be required to design zero-emission buildings by 2030. Since the late 20th century, computer tools have been continuously developed to enable architects to analyse the impact of their design decisions on user comfort (both visual and thermal), daylight availability, energy consumption, and, consequently, greenhouse gas emissions. Experts agree that decisions made during the early stages of the design process are crucial to the performance of a building, particularly in terms of user comfort and energy efficiency. During this phase, simulation tools should offer architects the opportunity to test various solutions, compare them, and select the optimal design. By utilising such tools, better informed design decisions can be made.

This article outlines the comprehensive architectural design process for a net-zero energy building using the latest computer-based building performance analysis tools. These tools are specifically developed with architects in mind, recognising the nature of architectural design. The results of the analyses are presented in an intuitive, graphical format, making them easily understandable for practitioners and users alike. Crucially, state-of-the-art simulation software fully leverages the capabilities of modern

computing, allowing analysis results to be generated within a time frame that enables architects to experiment with different design ideas.

Using the example of an office building concept, this paper details all the steps in the analytical process: the analysis of climatic conditions in the selected location; the selection of appropriate passive design strategies; the design of building massing to optimise daylighting within the spaces; the design of sunshades and the assessment of their impact on daylight availability and visual comfort; the analysis of energy consumption; and, finally, simulations to evaluate the potential for electricity generation via photovoltaic panels.

The analyses conducted have shown that contemporary computer simulation methods, techniques, and tools empower architects to address one of the most significant challenges in modern architectural design: the creation of net-zero energy buildings.

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