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Algorithmic energy retrofit model: Parametric optimization of indoor solar insolation

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Research Paper

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Algorithmic energy retrofit model: Parametric optimization of indoor solar insolation

Over the past 50 years, summer temperatures in Banja Luka have risen by about 2 °C, with peak values reaching 40.7 °C in July. This trend has led to a significant increase in cooling demand in public buildings, particularly in educational facilities, which represent 31.59 % of all public buildings in Bosnia and Herzegovina. Solar irradiation affects the interior comfort through glare, reflection, and overheating. A case study was conducted on an educational facility in Banja Luka using open-source climate data, sky matrices, and wind condition data. Thermal comfort was assessed via the universal thermal climate index (UTCI) during peak occupancy hours (08:00–16:00) in summer using open-source data. Using an algorithmic model, vertical exterior shading elements were defined according to the intensity of solar irradiation. Simulations in Rhinoceros with Grasshopper, Ladybug, and Honeybee analysed indoor solar irradiation with and without shading in an office space. The results indicated that parametrically optimised shading reduced the highest interior temperature, dispersed solar irradiation more evenly, and enhanced thermal comfort by integrating passive cooling solutions.

Key words:

building energy retrofit, overheating, window sunshades, office space, rhinoceros, grasshopper

Prethodno priopćenje

Slobodan Peulić, Milovan Kotur

Algoritamski model energetske obnove: parametarsko optimiranje osunčanja unutarnjeg prostora

Porast ljetnih temperatura, uključujući povećanje od 2 °C u posljednjih 50 godina u Banjoj Luci te ekstremne vrijednosti koje u srpnju dosežu 40,7 °C, znatno je povećao potrebu za hlađenjem u javnim zgradama. To je osobito važno za obrazovne ustanove koje čine 31,59 % ukupnih javnih zgrada u Bosni i Hercegovini. Solarno zračenje utječe na unutarnju udobnost izazivajući odsjaj, refleksiju i pregrijavanje. Studija slučaja jedne obrazovne ustanove u Banjoj Luci upotrebljava otvorene klimatske podatke, nebesku matricu i podatke o vjetru. Toplinska udobnost procjenjuje se pomoću Univerzalnog pokazatelja toplinske udobnosti (UTCI) tijekom najveće zauzetosti prostora (8.00 – 16.00) u ljetnome razdoblju. Algoritamskim je modelom definiran vertikalni vanjski element zasjenjenja u skladu s intenzitetom solarne zračenja. Simulacije u Rhinocerosu alatima Grasshopper, Ladybug i Honeybee analizirale su solarne zračenje unutar ureda s primjenom zasjenjenja i bez njega. Rezultati su pokazali da parametarski optimirano zasjenjenje smanjuje najvišu unutarnju temperaturu za 1,88 °C, ujednačeno raspršuje solarne zračenje te poboljšava toplinsku udobnost integracijom pasivnih rješenja za hlađenje.

Ključne riječi:

energetska obnova zgrada, pregrijavanje, sjenila za prozore, uredski prostori, rhinoceros, grasshopper

1. Introduction

A major challenge in developing countries such as Bosnia and Herzegovina is the prevalence of energy-inefficient building stock. This not only hinders efforts to combat climate change, but also exacerbates indoor comfort issues for occupants. On a broader scale, the construction sector is responsible for approximately 38 % of global greenhouse gas emissions [1], with the impact being particularly severe in countries where energy poverty is an escalating concern. Due to population growth and urbanization, energy consumption in buildings is showing an increasing trend, which is accompanied by a sharp increase in research focused on building energy consumption, CO₂ emissions, energy efficiency, emission control, and energy policy [2].

Energy poverty is defined as the inability to secure the energy necessary for adequate indoor heating [3–5]. However, most studies have focused primarily on winter conditions and failed to address the growing problem of summer-related energy poverty [6]. Recent research has highlighted that overheating during the summer is a widespread issue across Europe, even in countries with milder climates [7]. Furthermore, it is particularly critical in the southern regions. In Spain, for example, several studies have proposed incorporating cooling requirements into the definition of energy poverty [8]. Nevertheless, the focus remains largely on heating demands, while relevant laws, regulations, and strategies still lack comprehensive consideration of this issue. Summers in continental climate areas became warmer, with increased occurrence of heat waves and heavy rainfall as a result of global temperature increase [9], increasing the cooling demand ($Q_{c,nd}$). Since 1990, the energy consumption for space cooling has tripled, posing considerable challenges for electricity grids, increasing greenhouse gas emissions, and contributing to the formation of urban heat islands [10]. Some studies suggest that the energy used in HVAC systems accounts for approximately half of total energy consumption [11]. The absence of indoor cooling exposes a large portion of the world's population to the risk of heat stress, impacting thermal comfort, productivity, and overall

human health; furthermore, extreme climate events can be risky for society and ecosystems [12]. Hotter summers can increase the risk of energy poverty because higher outdoor temperatures increase the energy required for indoor cooling [13].

According to the IEA, the building floor area has increased by 60 % over the past two decades and is projected to increase by another 20 % this decade, adding a total floor surface area of nearly 45 billion m². More than half of this expansion has occurred in hot-climate regions that require space cooling but lack building energy codes covering the entire building sector. With global warming intensifying, air conditioning is expected to increase by 8 % by 2030 [14].

In the European Union, buildings accounted for 42 % of the energy consumed in 2021 and were responsible for 36 % of direct and indirect energy-related greenhouse gas emissions [15–17]. Even considering the large energy consumption in this sector, a large portion of buildings remain unrenovated owing to financial limitations, lack of knowledge of true benefits, or undeveloped support mechanisms and strategies. The European Union (EU) has set targets to reduce GHG emissions by at least 55 % by 2030 (from the current 40 %) and to achieve climate neutrality by 2050 [18]. The EU adopted a heating and cooling strategy in 2016 that underscored the importance of space cooling as a key aspect of thermal comfort in warmer climates [19]. This introduced a methodology to assess daily mean, minimum, and maximum temperatures relative to a baseline of 22 °C, above which buildings were assumed to require cooling. It linked excessive indoor heat to building quality and promoted renovation measures which could improve indoor environmental quality [20].

Global efforts have suggested three methods for reducing the energy required for cooling, with the aim of achieving zero net emissions by the year 2050: first, prioritizing passive cooling by new buildings with renewable materials or renovating existing ones; second, encouraging behaviour change, with occupants adopting optimal ways to reduce temperatures in offices (e.g., setting cooling points within the range of 24 to 25 °C) and third,

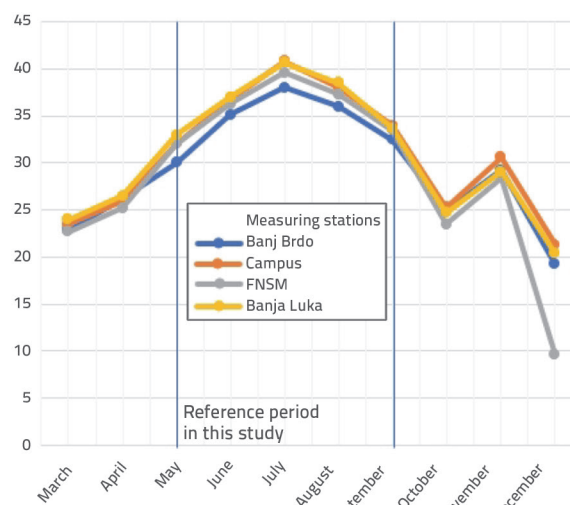
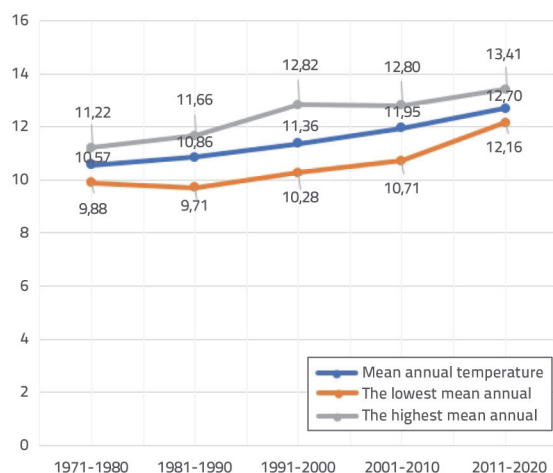


Figure 1. Increase in annual temperature (left) and absolute maximum air temperature in City of Banja Luka (right), based on data from [21, 22]

Table 1. Climate data for city of Banja Luka [26]

Parameter	Explanation	Unit	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Mean
AIR TEMPERATURE [°C]															
T mean	Mean (average) air temperature	°C	1.6	2.8	7.6	12.4	17	20.9	22.9	22.3	16.7	12.1	7.5	2.6	12.2
T standard deviation	Standard deviation of air temperature	°C	2.4	2.9	1.7	1.1	1.1	1.4	1.1	1.6	1.5	1.5	2.3	1.7	0.6
T minimum	Lowest recorded air temperature	°C	-23.5	-21.5	-18.2	-5.9	0.5	4.4	7.2	6.1	2.4	-5.5	-8.2	-18.2	-23.5
p1	1 st percentile temperature (very cold days)	°C	-1.7	-2.7	4.5	10.2	15	18.6	21.5	19.4	14.8	9.5	3.1	-1.5	10.8
p5	5 th percentile temperature	°C	-1.6	-2.1	5.5	10.7	15.6	19.2	21.7	19.5	14.9	9.8	3.3	0	11.2
p10	10 th percentile temperature	°C	-1.1	-1.8	6.0	11.0	15.9	19.5	21.7	20.1	15.1	9.9	3.9	1	11.5
p90	90 th percentile temperature (very warm days)	°C	5.3	6.5	9.5	13.8	18.6	22.9	24.6	24.2	18.8	13.8	10.4	4.5	12.8
p95	95 th percentile temperature	°C	5.8	6.7	10.0	14.1	18.9	23.3	25.2	24.4	19.2	14	10.9	4.6	12.9
p99	99 th percentile temperature (extremely hot days)	°C	6.1	7.0	11.0	14.2	18.9	23.9	25.2	24.4	20	14.2	11	4.6	13
T maximum	Highest recorded air temperature	°C	22.3	25.2	28.3	31.8	35.2	37.9	41.6	41.2	40.2	30.9	27.1	23.2	41.6
AIR HUMIDITY															
P mean	Mean monthly precipitation	mm	5.8	5.9	7.0	9.4	13.2	16.4	17.8	17.4	14.1	11.4	8.5	6.5	11.1
P07h	Precipitation at 07:00	mm	5.4	5.5	6.7	9.3	12.9	16.1	17.5	17	13.4	10.6	7.8	6	10.7
P14h	Precipitation at 14:00	mm	6.2	6.1	7.0	9.3	13.1	16	17.1	17.1	13.9	11.9	9.0	6.7	10.7
H srednja	Mean relative air humidity	%	84	79	69	68	70	69	61	68	75	80	82	85	75
H07h	Relative humidity at 07:00	%	89	89	85	84	82	80	79	83	89	92	90	90	86
H14h	Relative humidity at 14:00	%	80	75	66	64	64	62	60	61	70	75	77	80	68
WIND VELOCITY [m/s]															
W srednja	Mean wind speed	m/s	1.4	1.5	2.2	1.9	1.8	1.6	1.6	1.6	1.4	1.4	1.5	1.4	1.6

improving the efficiency of cooling devices used in both existing and newly built facilities [14].

As 58.32 % of the total energy supply of Bosnia and Herzegovina comes from coal thermal power plants, reducing energy consumption, especially in the construction sector, is especially critical. Bosnia and Herzegovina have adopted nationally determined contributions, setting unconditional goals to reduce GHG emissions by 12.8 % by 2030 and 50 % by 2050, relative to 2014 levels [20]. According to the NDC of the B&H, droughts are one of the most significant threats which cause economic, ecological, and social harm. The temperature

in the Banja Luka region has risen by 2°C over a 50-year period (Figure 1) [21, 22]. Furthermore, the peak temperature is occurring in month of July, reaching a maximum of 40.7°C in the urban area of the city.

Educational facilities constitute the largest share of public buildings by area, accounting for 31.59 %, followed by office and administrative buildings (27.49 %) and preschools (only 1.35 %). [23, 24], with most of them being constructed over the last 20 years [24]. Further analyses revealed a reduction in the transparent parts of the building envelope in favour of an opaque envelope.

Therefore, it is easier and cheaper to reduce the overall thermal transmittance coefficient (U-value) of the envelope. In public buildings, light comfort is highly important, especially in those where people spend a significant amount of time (kindergartens, primary and high schools, administrative buildings). Reducing the U-value by simply reducing the ratio of transparent to opaque parts is not optimal. Instead, it should be carefully reconsidered through improved glazing and frame capabilities, the use of shaders and/or special glass coatings, and better disposition and arrangement. The Strategy for Adaptation to Climate Change and Low-Emission Development of Bosnia and Herzegovina for the period of 2020–2030 presents an overview of energy consumption in public buildings based on their construction period and functional typology. According to this study, administrative buildings account for 36.3 % of all public buildings, while educational facilities represent 32 %; these two represent the largest number of public buildings. The highest energy requirement for heating was observed in kindergartens, followed by sports facilities and other categories [25]. However, the study did not address the cooling requirements of public buildings. For households, cooling was only indirectly considered through the overall annual electricity consumption. Despite being one of the most comprehensive national strategies, the document shows that cooling energy demand is still given far less importance than heating energy demand, highlighting a critical gap in energy planning.

According to Table 1, the highest temperature occurs in July, with mean of 22.9°C and peaks reaching up to 41.6°C [26], making cooling indispensable throughout operating hours.

Unlike residential buildings, which are occupied most of the time, public buildings experience both high occupancy periods and extended not-operational periods, such as weekends, holidays, and summer and winter breaks. Higher energy consumption for space cooling affects the peak electricity demand, especially during hot days, indicating that power outages might occur [10]. The current state of B&H's building stock results in inadequate or entirely absent cooling systems, compromising indoor comfort. In most cases, three cooling options are available: locally mounted air-conditioning units, windows shaded with blinds or covers on inner sides, and movable fans. Additionally, users often avoid using southern- and western-facing offices during peak temperatures. This demonstrates an inconsistent way of dealing with overheating issues in office spaces.

Reducing the need for active cooling through passive design strategies is one of the key measures for addressing the growing energy need for cooling ($Q_{c,nd}$) in public buildings.

The main parameters considered in this study were the reduction of direct solar exposure and optimisation of natural light distribution within the office spaces. By carefully controlling these factors, indoor air temperatures can be lowered during summer, thereby improving thermal comfort and decreasing the overall energy demand for cooling.

This approach requires an integrated design solution that not only limits the overheating caused by solar gains, but

also ensures adequate daylight availability, contributing to a healthier and more energy-efficient indoor environment. The optimisation of these conditions must be context-specific, considering the orientation, façade characteristics, glazing ratio, and occupancy patterns of the office space.

The following section explores simulation-based assessments and algorithmic approaches for evaluating and enhancing the thermal performance of selected office spaces in public sector buildings.

2. Analysing solar Irradiation and UTCI and developing an optimization algorithm for indoor office conditions

Public facilities often demand controlled heating, ventilation, air conditioning, and cooling systems to achieve optimal working conditions. There are several methods to reduce energy consumption in buildings, including building envelope performance enhancement, energy-efficient HVAC equipment, high-efficiency lighting systems, rational water consumption, renewable energy technologies, and intelligent control systems [27].

Regarding envelope improvements, it is possible to consider two approaches: regular and deep energy retrofitting [28, 29]. Both approaches aim to reduce the energy required for heating and cooling, increase the lifecycle of the building, and improve the indoor environment. According to the current regulations, walls must achieve a maximum of 0.30 W/m²K, roofs 0.20 W/m²K, and windows 1.60 W/m²K. Improvements in the transparent parts of the envelopes involve optimizing the window-to-wall ratio, supporting transparent parts on south-oriented façades, improving airtightness, and increasing thermal performance through multiple glazing, specialized coatings, and other measures.

There is growing literary interest in improving building energy efficiency by controlling overheating, particularly in the context of climate change and increasing cooling demand. However, most existing studies and methods focus on the analysis of opaque building envelopes; hence, the issue of overheating caused by solar radiation through windows remains underexplored. Methods addressing window surfaces are limited and often do not provide a comprehensive assessment of the dynamic behaviour under real conditions. In addition, holistic and interdisciplinary methodologies combining architectural design, glazing typologies, and passive solar protection systems are lacking.

Recent comparative studies between traditional and bioclimatic buildings [30–34] demonstrate the positive influence of integrated passive strategies in maintaining indoor thermal comfort [35], with overheating reduced by more than 50 % in nearly all regions [36]. For example, external shading in the Passiv Haus building in Slovenia facilitated the maintenance of indoor temperatures between 20 and 25°C during August [37]. A similar study used a south-oriented shading control strategy and showed that maintaining 70 % shading during

warm periods significantly reduces the cooling demand [38]. Shading systems with automated control outperform manual systems and minimise overheating [39, 40]. The importance of external shading on insulated office buildings shows promising results in reducing the energy required for cooling; however, with increasing heating and lighting demands, these systems are more effective in hot climates [41, 42].

This paper presents a possible method to optimise indoor conditions by implementing easy-to-install solutions for windows that tackle interior solar insolation. Achieving this requires software capable of simulating the current conditions and identifying problems based on the universal thermal climate index (UTCI), exploring potential solutions, and analysing results. Building Performance Simulation software can support this process via optimisation, which involved defining complex algorithms to identify variables and constraints, establishing objectives, and running simulations to find solutions [43].

The generated algorithm is tested on a specific example of a university building and on inputs from open-source climate index parameters for the specified location, with the aim of reducing the interior temperature during summer, when outdoor temperatures are highest. The entire process was automated without manual design decisions and was easily adjustable.

2.1. Thermal climate index (TCI) application in energy design

Heat stress impacts human behaviour, health, and performance. Various climatic parameters, including temperature, air humidity, wind velocity, and solar radiation, play crucial roles in shaping the physical and psychological perceptions of indoor environments. Thermal comfort is usually evaluated by the subjective feelings of a certain number of questionnaires (at least 1300). According to BAS EN ISO 7730, within the FANGER method [44], indoor comfort can be described using the predicted mean vote (PMV), which reflects the mean opinion on indoor comfort, and predicted percentage of dissatisfied (PPD), which considers the percentage of people dissatisfied with the indoor climate [45]. The European Standard EN 15251 suggests design ranges of operative temperatures that are in line with the acceptable level of thermal comfort. Consequently, the accurate calculation of the PMV, PPD, and relevant operative temperature is crucial for indoor environmental quality (IEQ) and energy savings [46-48]. According to ISO 7730 [45], an environment can be considered thermally comfortable if 80 % of its users feel neutral or pleasant [48].

For example, temperature and humidity are key elements that influence the perception and tolerance of heat. High temperatures and elevated humidity levels can cause discomfort and strain the body's ability to cool, leading to conditions such as heat exhaustion and heat strokes. Solar radiation also contributes to the thermal dynamics of indoor spaces by influencing the temperature and light levels, which affect how people experience their surroundings.

These climatic influences are perceived differently depending on personal factors, such as clothing, activity level, and individual heat tolerance. Researchers have created several indices to systematically understand and quantify subjective thermal perceptions. These indices translate complex climatic interactions into measurable values, allowing for an objective assessment of thermal comfort and heat stress. Some widely used indices include the wet-bulb globe temperature, heat index, and universal thermal climate index, which integrates multiple meteorological parameters to evaluate thermal conditions. This study focuses on software that uses outside temperature parameters; hence, both Wet Bulb Globe Temperature - WBGT and Universal Thermal Climate Index - UTCI were calculated based on it. These indices are valuable in designing and maintaining indoor environments that support health, comfort, and efficiency. By using these, it is possible to tailor climate control strategies that mitigate the negative effects of heat stress, enhance the indoor climate experience, and support optimal human performance and well-being.

The UTCI, which was introduced in 1994, incorporates dry temperature [49], relative humidity, solar radiation, and wind speed. It is recognised as the benchmark environmental temperature that causes discomfort [50]. This study was supported by the International Society of Biometeorology and COST Action 730 [49, 51].

The standard effective temperature is a logical and thorough comfort temperature indicator derived from two physiological factors, namely skin temperature and wetness [52].

The UTCI is considered the most comprehensive index used to define thermal comfort. It is defined as the air temperature of the reference environment which produces the same strain index value as that of a reference individual's response to the real environment. It is regarded as one of the most comprehensive indices for calculating heat stress in outdoor spaces [53]. The parameters that are considered for calculating the UTCI include dry temperature, mean radiation temperature, the pressure of water vapour or relative humidity, and wind speed (at an elevation of 10 m) [46].

2.2. Integrating evolutionary algorithms into parametric energy modelling using open-source climate data

The recent development of parametric/algorithmic software has promoted design flows based on algorithmic processes, sets of commands, and data inputs, in contrast to conventional direct manipulations within CAD or BIM models. In recent years, computer-aided design has been adopted worldwide for greater efficiency in terms of design possibilities, time and cost savings, and predictability in the design phase of real-life situations [54]. These simulations gather advanced weather data to simulate indoor/outdoor environments, building energy performance, and human biological reactions to these parameters. Hence, algorithmic software can contribute to three types of simulations. The first focuses on weather conditions such as

sun path, solar irradiation, wind frequency, wind velocity, and air humidity. The second predicts the effects and scenarios of built environment behaviour based on previously defined models. The third simulates complex human metabolic reactions to these conditions.

Parametric modelling environments such as Rhinoceros and Grasshopper, combined with simulation tools such as Ladybug and Honeybee, provide a strong foundation for energy performance analysis. Designers can define variables such as window size, shading depth, and facade orientation in Grasshopper. Ladybug and Honeybee simulate solar exposure, daylight access, and energy loads. These outputs are then used as criteria to evolve the optimal configurations. This method is particularly effective for reducing the cooling demand in areas with high solar gain and balancing thermal comfort and daylighting.

The workflow in this study employs contemporary software solutions based on algorithmic thinking, enabling automated process for the creative definition of architectural structures. Rhinoceros and Grasshopper represent a switch in the design paradigms set by CAD and BIM software, as they are based on mathematical and programming workflows. Rhinoceros is as a standard 3D software that allows the creation of simple and complex geometries; however, with the addition of a Grasshopper plug in the design process, it evolves into a powerful engine which can perform advanced energy simulations. These simulations are an integral part of architectural design that is becoming data-based. The general idea behind the parametric design is to use mathematical algorithms to optimise certain design goals against a set of design constraints [43]. Today, software plugins such as Grasshopper can simulate environmental and building energy performance; however, the capacities and applications of these plugins are still not widely used, leaving considerable scope for further research on their capabilities and integration into everyday practice. Moreover, clear instructions for using these plugins are limited.

Solar radiation analyses and outdoor comfort calculations were performed to assess the environmental performance of different building types. These evaluations were performed using the Ladybug and Honeybee tools, which were seamlessly integrated into Rhinoceros 3D and Grasshopper. Ladybug tools specialise in environmental design, simulating sun exposure, and shadow studies, whereas Honeybee facilitates simulations of energy demand and microclimates. By integrating these analyses and utilising lifetime feedback, various scenarios can be optimised, thereby enhancing the overall design quality. [55, 56].

The outdoor comfort calculator component from Ladybug requires building geometry and weather files. EnergyPlus utilises an Energy Plus Weather file for any location, which is accessible as an open-source download [57]. Analyses can span a full year or specified period. This component yields the UTCI, individual stress level, and percentage of time that the space remains comfortable. The UTCI, measured in degrees, encapsulates the impact of weather on individuals, factoring in solar radiation, humidity, and wind speed [56].

Ladybug's reliability is supported by its foundation, which is based on multiple scientifically recognised software packages, such as Radiance, EnergyPlus/OpenStudio, Therm/Window, and OpenFOAM [58]. In the architecture, engineering, and construction (AEC) industry, this tool can be used to perform comprehensive climate analyses and thermal comfort studies on both micro (facilities) and macro (neighbourhood) scales, with possible scaling from simulations of workspace conditions to analysis of heat islands in cities, disposition between buildings, and related factors.

HoneyBee is another tool from the same software architecture. It is based on the simulation capabilities of Ladybugs and is used in the later stages of design; specifically, it creates, runs, and visualises daylight and radiation simulations using Radiance, as well as energy models using EnergyPlus/OpenStudio [59]. Its application facilitates illuminance studies, annual daylight studies (used in this study), glare analyses, and thermal comfort analyses.

Thermal comfort models and indices are important in the analysis of the relationship between the human body and ambient environment [60]. In practice, there are several methods for evaluating thermal comfort standards, such as effective temperature [61], perceived temperature, physiologically equivalent temperature, and the universal thermal climate index [62]. Both PET and UTCI show great reliability in research, and their indices are measured in degrees Celsius, making them easily understandable even for the general public and practitioners outside the AEC industry [62]. The universal thermal climate index is an equivalent temperature (°C), which is the measure of the human physiological response to the thermal environment [63].

In multiple studies, the UTCI has been found to be the most reliable in the widest range of climates [59]. The UTCI accounts for self-adaptation regarding clothes and activity, making it suitable for studies of general population [62]. Unlike PET, it does not require inputs about clothing type and the metabolic rate of the user.

The calculations used in this study were based on Open-Source Climate Data from ASHRAE. First, a universal thermal climate index (UTCI) was calculated for the case study of a university complex in Banja Luka. Based on that data, further environment and building performance simulations were performed using the Ladybug tool in Grasshopper. By definition, the UTCI requires inputs for air temperature, relative humidity, wind speed and radiation fluxes [62]. All these parameters are contained within the EPW file used in this study.

2.3. Defining the algorithm for case study of an educational facility in Banja Luka

The algorithm is used the climate data of the city of Banja Luka from 2007 to 2021, provided as an EPW file under the ASHRAE licence. The sun path was defined for irradiation simulation during a specified period (Figure 3). Hours of the year (HOYS)

were defined for the warmest period of the year (Table 1), from May 1 to September 30 (Figure 2). Furthermore, calculations were limited to specific periods of highest occupancy in buildings, from 8:00 to 16:00. The simulations also considered other properties, such as cloudiness (sky matrix) and wind. A similar approach was applied in a previous study, with simulations limited to operational hours from 8:00 to 15:00 and August excluded owing to building closure [64]; however, here, the entire period is considered owing to the occasional occupancy of the analysed office.

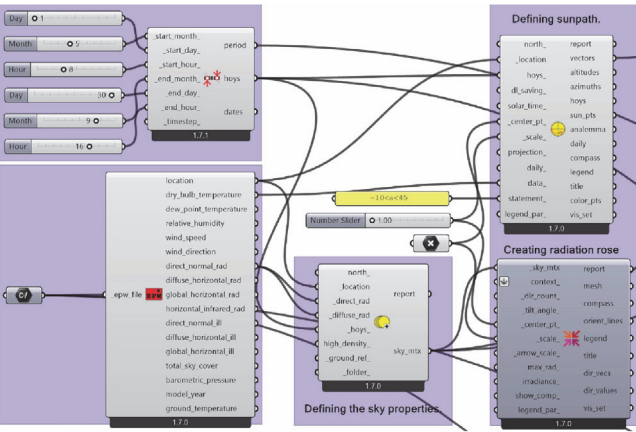


Figure 2. Input parameters used for thermal simulation

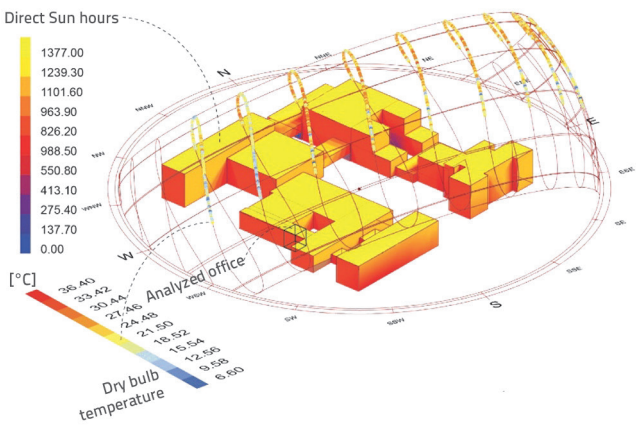


Figure 3. Sun-path diagram defined with the Ladybug tool in Grasshopper (City of Banja Luka; 1.5. to 30.9; 8 to 16 h)

The following sun path diagram uses the dry-bulb temperature, commonly known as the air temperature, which is the most frequently referenced air property. This term was used because the measurement was performed using a thermometer that was unaffected by air moisture. The dry-bulb temperature is measured using a standard thermometer that is freely exposed to air but shielded from radiation and moisture. It is typically expressed in degrees Celsius (C) or Fahrenheit (°F) [49]. An algorithmic model was developed for the further analysis of the solar impact and detection of predominantly insulated parts of the building. The sun path defined for this period revealed

reduced solar exposure on southern walls owing to newly erected residential buildings. However, west-oriented façade walls remain fully exposed to direct irradiation and therefore represented a priority for interventions. Besides orientation, important factors in prioritising intervention include the time and level of occupancy, type of work, and spatial volume.

2.4 UTCI analysis of office space considering optimal temperatures for concentration

This study assessed a typical office space in a building at the Faculty of Technology. The university complex was established between 1970 and 1980 and is currently in a state requiring excessive renovation measures. Over time, educational complexes often deteriorate due to faults resulting from either design flaws or material aging. In this example, almost all signs of poor facility management are present, such as façade decay; thermal bridges from poorly designed details; flat roof leakage; deteriorated mechanical, electric, and plumbing systems; air infiltration at connections between the locksmith and walls; and overall functional decline. Addressing these issues requires a comprehensive program of adaptation, retrofitting, and reprogramming.



Figure 4. Case study: Office space window at the Faculty of Technology in Banja Luka

The following sun path diagram uses the dry-bulb temperature, commonly known as the air temperature, which is the most frequently referenced air property. This term was used because the measurement was performed using a thermometer that was unaffected by air moisture. The dry-bulb temperature is measured using a standard thermometer that is freely exposed to air but shielded from radiation and moisture. It is typically expressed in degrees Celsius (C) or Fahrenheit (°F) [49]. An algorithmic model was developed for the further analysis of the solar impact and detection of predominantly insulated parts of the building. The sun path defined for this period revealed reduced solar exposure on southern walls owing to newly erected residential buildings. However, west-oriented façade walls remain fully exposed to direct irradiation and therefore

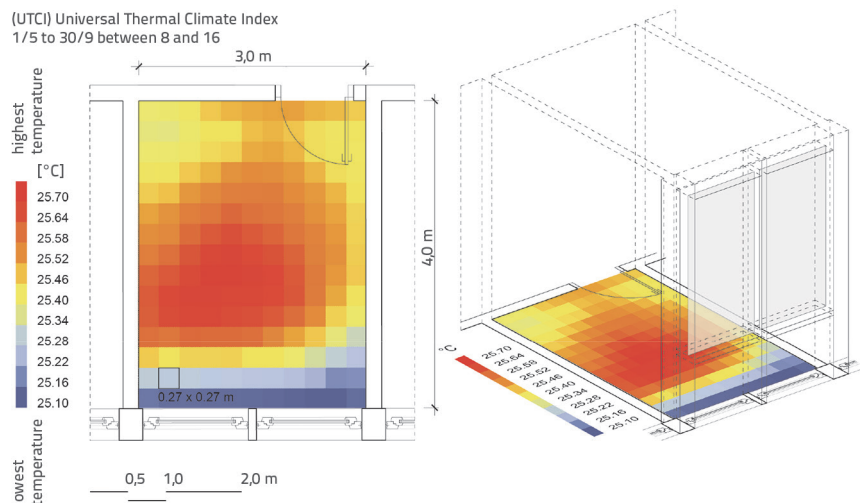


Figure 5. UTCI analysis of the west-oriented office spaces without window-shading devices

represented a priority for interventions. Besides orientation, important factors in prioritising intervention include the time and level of occupancy, type of work, and spatial volume.

For experimental purposes, a typical office space measuring 12 m² and oriented westward was utilised (Figure 4). This office did not have any natural or constructed sun barriers, causing it to be fully exposed to direct sunlight. Previous analyses have shown that western-facing walls receive 963.90–1101.60 h of direct sunlight during the analysed period. As a result of this prolonged exposure, the UTCI within the office ranged between 25.10 and 25.70°C (Figure 5).

These values fall within the range prescribed by ASHRAE Standard 55, which defines the comfort zone to be between 22.8 and 26.1°C [65]. However, it should be noted that both May and September, which have milder weather conditions compared to peak summer, were included in the calculation (Table 1 and Figure 1).

In comparison with other studies, thermal comfort thresholds in Australia are defined within the range of 20–24°C, specifically 21.5°C ± 1.5°C in winter and 22.5°C ± 1.5°C in summer [65]. Furthermore, research has shown that temperatures above 25.7°C can negatively affect cognitive performance and lead to a decline in users' concentration [67]. Another study comparing cognitive performance at two set temperatures found that at 22°C, cognitive functions were more stable and even stimulated, whereas at 24°C, a slight decline in concentration was observed [67].

Considering the presented values and milder climate conditions in May and September, we can conclude that, although the recorded temperatures formally fall within the ASHRAE-defined comfort range (22.8–26.1°C), findings from other studies suggest that temperatures exceeding 25.7°C may impair cognitive performance. This highlights the need for a more precise approach for defining optimal indoor conditions, especially in the context of climate change and increasingly frequent heat events.

A significant issue identified in this analysis was the formation of a concentrated heat zone in the middle of the office. This uneven distribution of heat not only affects the comfort of the occupants, but also potentially impacts the efficiency of the cooling systems. Therefore, future interventions should address this issue by implementing measures that ensure a more uniform temperature distribution throughout the room.

Potential strategies for achieving an even temperature distribution include the following:

Installation of reflective window films or shades to reduce heat gain

Application of fans or air circulation systems to disperse hot air more evenly

Installation of passive cooling elements, that is window shades, to lower direct sun exposure in interior space

Addressing these heat distribution challenges can create a more comfortable and energy-efficient office environment, reduce hotspots, and ensure stable and pleasant temperatures across the entire space.

3. Results-assessing the solution impact on indoor solar irradiation

Heat gains occur because of solar radiation, heat transmission through the envelope, infiltration of outdoor air, occupants' metabolic temperature, heat emissions due to lightning, machines, and other processes (cooking, ironing, etc.). Solar heat gains through the transparent parts of the envelope were shown to be the main source of excessive cooling loads, especially if the envelope was oriented towards the south and west. According to Hardy and Mitchell, for heavy weight structures (such as the one in this case study), the maximum percentage of glazing compared with the opaque part of the wall should be 70 % in the case of air conditioning or 45 % in the case of mechanical ventilation [68]. However, existing facilities do not have either type of indoor air quality control devices; therefore, overheating is inevitable. Reducing the window area requires construction interventions, and this can reduce the visual comfort in offices. Several potential solutions, such as external and internal shading devices, blinds with double glazing, and various types of glass coatings, are feasible.

To mitigate overheating inside the office space, an external shading device was developed as a potential solution for further analysis. These devices were fixable, adjustable, and retractable, and they were designed to prevent direct radiation at appropriate times of the day and year [69]. Therefore, they were optimised to allow solar gains during winter, while preventing direct sunlight during five months of high solar radiation.

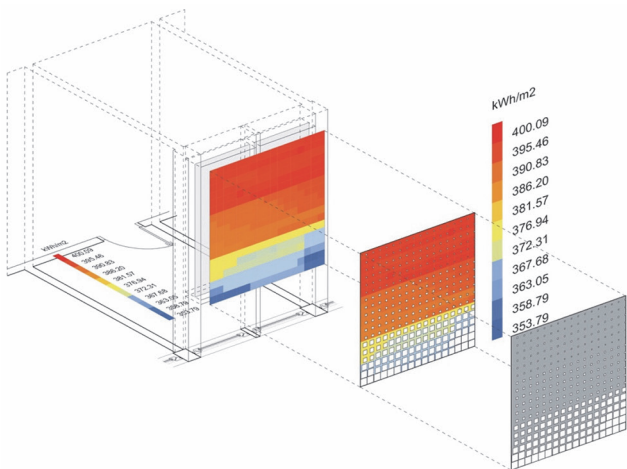


Figure 6. Radiation analysis of a shader with a parametric definition of perforation

Solar radiation was analysed using the Honeybee tool in Grasshopper, revealing the exact insolation patterns on the shading plate during the analysed period. The results indicate that the lower parts of the plate were less affected by the sun, whereas the upper parts were mostly insulated (Figure 6). In this analysis, a vertical shading plate was designed to allow more light to pass through the less insulated part and prevent direct sunlight from passing through the upper parts of the panel. The parametric definition of the shade is shown in Figure 7, where it is evident that irradiation outcomes on a planar surface (kWh/m^2) are converted to units ranging from 0 to 1, with 0 representing the minimal area of the physical surface of the shader (widest open square for light) and 1 representing the maximum area of the physical surface of the shader (smallest open square for light). In this case, the sill height is 1.00 m, and the height of the panel is 3.00 m. Highest percentage of perforation aligns with the occupant's eye when seated (working), providing necessary visual comfort and communication with the outer space. After developing the algorithm and establishing a new shader perforation arrangement, a comprehensive parametric analysis was performed to evaluate the thermal performance of the system. This analysis aimed to illustrate how heat is dispersed across the surface and

assess its impact on the heat island effect in the surrounding environment. The algorithm creation phase involved complex computational procedures to ensure that shader perforations were designed optimally. These perforations play a crucial role in controlling the amount of sunlight that penetrates the surface, thereby influencing thermal dynamics. By carefully adjusting the size, shape, and distribution of these perforations, the algorithm ensures that the maximum amount of heat is either absorbed or reflected in a manner that minimises excessive heat accumulation. Following the implementation of the shader perforation design, a parametric analysis was performed. This involved systematically varying the parameters to observe their effects on the heat distribution and identify the most efficient configuration. Advanced simulation tools were used to model the thermal behaviour, providing detailed visualisation and data on how heat moves through the shaded surface.

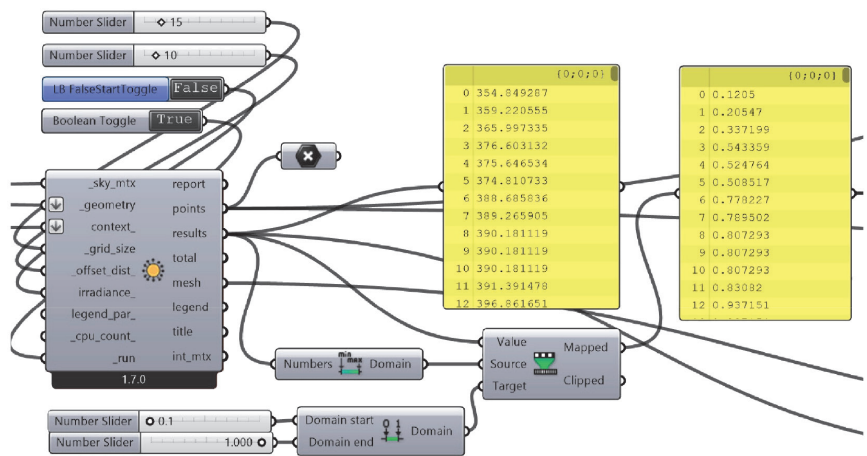


Figure 7. Part of the algorithm with visible conversion of solar irradiation (left yellow panel) into the shader-opening scale factor (right yellow panel)

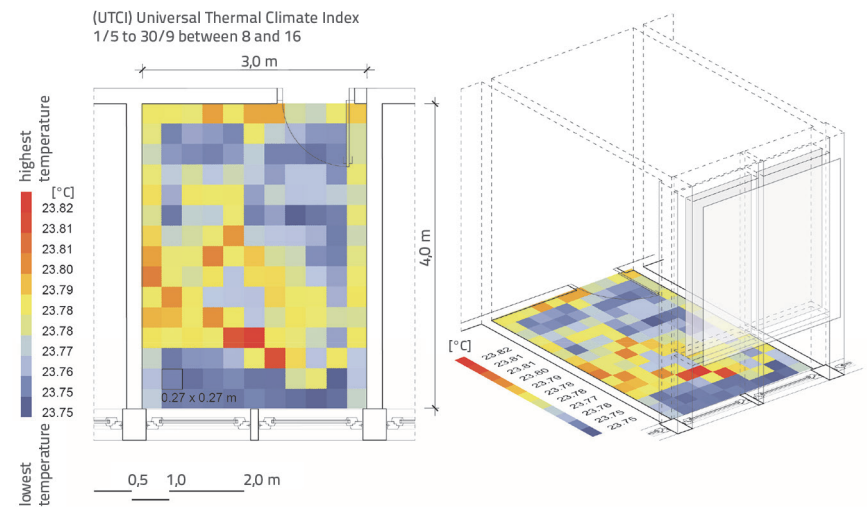


Figure 8. UTCI analysis of typical office space after installation of the outer shading device

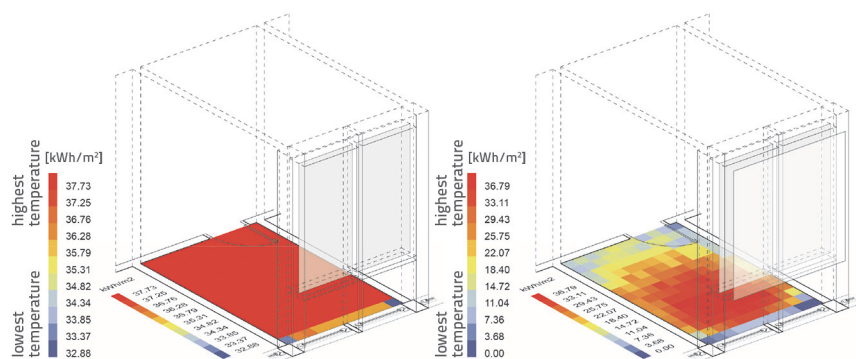


Figure 9. Incident irradiation in the office space before (left) and after (right) installation of the shading device

Using this methodology, the indoor thermal comfort was improved by reducing the solar gains during summer months (Figure 8). Notably, the maximum room temperature decreased by 1.88°C, highlighting the practical advantages of employing computational tools for building design and optimisation. The UTCI analysis demonstrated that, following the installation of the shading device, the temperature distribution within the office became more uniform, effectively eliminating the previously concentrated heat zone at the centre of the space.

The link between the reduced room temperature, improved thermal comfort, and decreased cooling energy demand is crucial. By creating a more comfortable indoor environment through the effective management of indoor solar irradiation, it is possible to reduce reliance on mechanical cooling systems, resulting in energy savings and environmental benefits.

For a more detailed assessment, incident radiation on the office floor was analysed further (Figure 9). The results showed a significant reduction in irradiation compared to the state without the shading device, with irradiation reduced to zero in the corners of the office and significantly decreased along the areas adjacent to the walls.

Through this process, the results obtained from the parametric analysis not only demonstrate the effectiveness of the shader design for indoor solar irradiation, but also provide valuable insights for further optimisation. These findings can contribute to the development of more efficient passive architectural solutions that can significantly improve the urban thermal comfort and reduce the negative impacts of overheating.

4. Conclusion

This study introduces an architectural design approach based on mathematical and parametric principles. The proposed solution is algorithmic. It utilises open-source climate data, including solar irradiation, sky matrix, and wind, and offers a flexible and scalable method that is adaptable to a variety of scenarios. A case study was conducted on an educational facility in Banja Luka, with simulations conducted using Rhinoceros software combined with the Grasshopper, Ladybug, and Honeybee

plugins. The analysis was limited to peak occupancy hours (08:00–16:00), and thermal comfort was evaluated using the UTCI, which ranged between 25.10 and 25.70°C.

The developed vertical shading panel, parametrically defined according to the solar irradiation falling on its surface, proved to be a pivotal initial step in mitigating thermal discomfort. A comparative analysis of the indoor solar irradiation with and without the shading system confirmed its effectiveness. The design reduced the interior temperature by 1.88°C, demonstrating how passive,

algorithmically driven solutions can enhance thermal comfort while reducing reliance on mechanical cooling.

While the panel represents foundational interventions, further development can substantially increase its impact. Future research should focus on optimising the panel's distance from the façade, angle, and segmentation, as well as on the integration of motorised or dynamic systems. These refinements can enhance the performance and potentially eliminate the need for traditional air-conditioning systems.

This study not only emphasises the immediate benefits of the proposed shading solution, but also suggests broader applications. Extending the algorithm can enable significant improvements in HVAC efficiency, humidity control, airflow management, and artificial lighting distribution, supporting a more integrated and sustainable approach for environmental control in architectural spaces.

In summary, this study offers a comprehensive framework for addressing thermal comfort in hot climates by integrating advanced algorithmic designs with practical passive architectural solutions. The continued development and application of these methods can redefine traditional architectural practices, fostering environments that are both energy-efficient and supportive of occupant health, performance, and comfort. Although the presented simulation results demonstrated the effectiveness of passive shading strategies in reducing overheating in office spaces, further exploration is required to evaluate the robustness of the proposed solution under varying conditions. In this study, fixed parameters were used to illustrate the performance before and after the application of a shading device. However, a comprehensive parameter sensitivity analysis was not conducted, which represents a known limitation of this study. Future research should focus on assessing how variations in inputs such as shading depth and angle, window-to-wall ratio, glazing properties, internal heat gains, and ventilation rates affect the thermal comfort and overheating levels. Such analyses will help identify the most influential design parameters and enhance the reliability and adaptability of the proposed passive measures across different office typologies and climatic contexts.

REFERENCES

- [1] Eurostat: Energy efficiency in buildings, <https://ephtinktank.eu/2016/07/08/energy-efficiency-in-buildings/>, [1.3.2024.]
- [2] Churchill, S.A., Smyth, R., Farrell, L.: Fuel poverty and subjective wellbeing, *Energy Economics*, 86 (2020).
- [3] Zohra Filali F., Zohra Chafi F.: Potrošnja energije i emisije CO₂ u zgradama: bibliometrijski pregled trendova, izazova i budućih smjernica, *Građevinar*, 77 (2025) 4, pp. 367–380, doi: <https://doi.org/10.14256/jce.4264.2025>
- [4] Biermann, P.: How fuel poverty affects subjective well-being: Panel evidence from Germany, 2016.
- [5] Kahouli, S.: An economic approach to the study of the relationship between housing hazards and health: the case of residential fuel poverty in France, *Energy Economics*, 85 (2020).
- [6] Igawa, M., Piao, X., Manag, S.: The impact of cooling energy needs on subjective well-being: Evidence from Japan, *Ecological Economics*, 198 (2022).
- [7] Morgan, C., Foster, J.A., Poston, A., Sharpe, T.R.: Overheating in Scotland: contributing factors in occupied homes, *Building Research & Information*, 45 (2017).
- [8] Sánchez-Guevara Sánchez, C., Mavrogiani, A., Neila González, J.: On the minimal thermal habitability conditions in low income dwellings in Spain for a new definition of fuel poverty, *Building and Environment*, 114 (2017), pp. 344–356
- [9] Trkulja T., Radujković, M., Nikolić-Topalović, M.: Sustav vertikalnog ozelenjavanja - model za poboljšanje energetske učinkovitosti zgrada, *Građevinar*, 74 (2022) 7, pp. 561–571, <https://doi.org/10.14256/JCE.3370.2021>
- [10] International Energy Agency: Tracking space cooling, <https://www.iea.org/energy-system/buildings/space-cooling/>, [1.3.2024.]
- [11] Kalfaoglu Hatipoglu H., Cetin R., Hatipoglu A.: Održivo stanovanje: Analiza energetske učinkovitosti u Turskoj u usporedbi s austrijskim građevinskim standardima, *Građevinar*, 74 (2022) 8, pp. 647–659, <https://doi.org/10.14256/JCE.3332.2021>
- [12] Intergovernmental Panel on Climate Change (IPCC): Managing the risks of extreme events and disasters to advance climate change adaptation: A special report of working groups I and II of the Intergovernmental Panel on Climate Change, https://www.ipcc.ch/site/assets/uploads/2018/03/SREX_Full_Report-1.pdf, [1.3.2024.]
- [13] Thomson, H., Simcock, N., Bouzarovski, S., Petrova, S.: Energy poverty and indoor cooling: An overlooked issue in Europe, *Energy and Buildings*, 196 (2019), pp. 21–29
- [14] International Energy Agency: Key energy statistics - Bosnia and Herzegovina, <https://www.iea.org/countries/bosnia-and-herzegovina/>, [1.3.2024.]
- [15] European Parliament: EU Directive 2023/1791 of the European parliament and of the council of 13 September 2023 on energy efficiency and amending regulation (EU) 2023/955, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ%20%3AJOL_2023_231_R_0001&qid=1695186598766, [1.3.2024.]
- [16] European Parliament: EU Directive 2024/1275 of the European Parliament and of the Council of 24 April 2024 on the energy performance of buildings (recast), https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L_202401275&pk_keyword=Energy&pk_content=Directive, [1.3.2024.]
- [17] Sesana, M.M., Salvalai, G., Della Valle, N., Melica, G., Bertoldi, P.: Towards harmonising energy performance certificate indicators in Europe, *Journal of Building Engineering*, 95 (2024), p. 110323
- [18] European parliament: Reducing carbon emissions: EU targets and policies, European Green Deal, <https://www.europarl.europa.eu/topics/en/article/20180305STO99003/reducing-carbon-emissions-eu-targets-and-policies/>, [1.3.2024.]
- [19] European Commission: An EU Strategy on Heating and Cooling, Brussels, 2016.
- [20] Nationally determined contributions for Bosnia and Herzegovina (NDC) for the period 2020 – 2030, https://climate-laws.org/document/bosnia-and-herzegovina-first-ndc-updated-submission_71c1, [7.4.2024.]
- [21] Okilj, U., Čvoro, M., Čvoro, S., Uljarević, Z.: The green dimension of a compact city: Temperature changes in the urban area of Banja Luka, *Buildings*, 13 (2023).
- [22] The Hydrometeorological Institute of the Republic of Srpska, <https://www.rhmzrs.com/>, [31.5.2023.]
- [23] Nišandžić, M.: Typology of Public Buildings in Bosnia and Herzegovina, UNDP in Bosnia and Herzegovina, Sarajevo, Bosnia and Herzegovina, 2018.
- [24] Hadžikadić, E.: Typology of public buildings in Bosnia and Herzegovina, Proceedings of The 4th Energy summit in Bosnia and Herzegovina, https://www.energy-community.org/dam/jcr:1bac2ed9-9f87-4fd6-ab69-c6a75ff40a5e/EECG_UNDP_BH_062018.pdf, [21.3.2024.]
- [25] The Strategy for adaptation to climate change and low-emission development of Bosnia and Herzegovina for the period 2020 – 2030, UNDP, https://unfccc.int/sites/default/files/resource/ENG_CC_%20adaptation_%20and_%20Low_%20emission_%20development_%20Strategy_%20BiH_%202020-2030.pdf, [15.4.2024.]
- [26] Ministry of Spatial Planning, Civil Engineering and Ecology: Rulebook on energy survey and energy certificate publication, Official Gazzete of The Republic of Srpska 40/13, Banja Luka, 2015.
- [27] Yi, C., Bing, X.: Encyclopedia of sustainable technologies, 2017.
- [28] Gajić, D., Peulić, S., Mavrić, T., Sandak, A., Tavrzes, Č., Malešević, M., Slijepčević, M.: Energy retrofitting opportunities using renewable materials - Comparative analysis of the current frameworks in Bosnia-Herzegovina and Slovenia, *Sustainability*, 13 (2021).
- [29] Peulić, S., Gajić, D., Mitrović, Z.: Reliability of experimental methods to determine heat transmission coefficient of the existing building façade wall, *Thermal Science*, 29 (2025), pp. 2185–2197
- [30] Camara, T., Kamsu-Foguem, B., Diourte, B., Issa Maïga, A., Habbadi, A.: Management and assessment of performance risks for bioclimatic buildings, *Journal of Cleaner Production*, 147 (2017).
- [31] Katsaprakakis, D., Georgila, K., Zidianakis, G., Michopoulos, A., Psarras, N., Christakis, D., Condaxakis, C., Kanouras, S.: Energy upgrading of buildings. A holistic approach for the Natural History Museum of Crete, Greece, *Renewable Energy*, 114 (2017), pp. 1306–1332
- [32] Pajek, L., Košir, M.: Implications of present and upcoming changes in bioclimatic potential for energy performance of residential buildings, *Building and Environment*, 127 (2018), pp. 157–172
- [33] Soutullo, S., Sanchez, M.N., Enriquez, R., Olmedo, R., Jimenez, M.J., Heras, M.R.: Comparative thermal study between conventional and bioclimatic office buildings, *Building and Environment*, 105 (2016), pp. 95–103

- [34] Soutullo, S., Sanchez, M.N., Enriquez, R., Olmedo, R., Jimenez, M.J.: Bioclimatic vs. conventional building: experimental quantification of the thermal improvements, *Energy Procedia*, 122 (2017), pp. 823-828
- [35] Puertolas Felices, R., Losada Gonzalez, J.C., Soutullo Castro, S., Aguilera Benito, P., Vinas Arrebola, C.: A bioclimatic building in Madrid: Analysis of the thermal response and long-term comfort indices review, *Developments in the Built Environment*, 3 (2020)
- [36] Harkouss, F., Fardoun, F., Biwole, P.H.: Passive design optimisation of low energy buildings in different climate, *Energy*, 165 (2018), pp. 591-613
- [37] Mlakar, J., Štrancar, J.: Overheating in residential passive house: Solution strategies revealed and confirmed through data analysis and simulations, *Energy and Buildings*, 43 (2011), pp. 1443-1451
- [38] Wang, Y., Kuckelkorn, J., Zhao, F., Spliethoff, H., Lang, W.: A state of art of review on interactions between energy performance and indoor environment quality in Passive House buildings, *Renew. Sustain. Energy Rev.*, 72 (2017), pp. 1303-1319
- [39] Ip, K., Lam, M., Miller, A.: Shading performance of a vertical deciduous climbing plant canopy, *Build. Environ.*, 45 (2010), pp. 81-88
- [40] Hammad, F., Abu-Hijleh, B.: The energy savings potential of using dynamic external louvers in an office building, *Energy Build.*, 42 (2010), pp. 1888-1895
- [41] Bellia, L., De Falco, F., Minichiello, F.: Effects of solar shading devices on energy requirements of standalone office buildings for Italian climates, *Appl. Therm. Eng.*, 54 (2013), pp. 190-201
- [42] Figueroa-Lopez, A., Arias, A., Oregi, X., Rodriguez, I.: Evaluation of passive strategies, natural ventilation and shading systems, to reduce overheating risk in a passive house tower in the north of Spain during the warm season, *Journal of Building Engineering*, vol. 43 (2021)
- [43] Chi, D., Gonzalez, E., Valdivia, R., Gutierrez, E.: Parametric design and comfort optimization of dynamic shading structures, *Sustainability*, 13 (2021).
- [44] Fanger, P.O.: Thermal comfort - Analysis and applications in environmental engineering, Danish Technical Press Copenhagen, 1970.
- [45] International Standardization Organization: ISO 7730:2005: Ergonomics of the thermal environment — Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria, 2005.
- [46] Zare, S., Hasheminejad, N., Shirvan, H.E., Hemmatjo, R., Sarebanzadeh, K., Ahmadi, S.: Comparing Universal Thermal Climate Index (UTCI) with selected thermal indices/environmental parameters during 12 months of the year, *Weather and Climate Extremes*, 19 (2018), pp. 49-57
- [47] European Commission: EN 15251: Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics, Brussels, 2007.
- [48] Gajić, D., Stupar, D., Antunović, B., Janković, A.: Determination of the energy performance indicator of kindergartens through design, measured and recommended parameters, *Energy and Buildings*, 204 (2019).
- [49] National Weather Service: Temperatures including dry bulb/ wet bulb/ dew point/ potential/ equivalent potential, https://weather.gov/source/zhu/ZHU_Training_Page/definitions/dry_wet_bulb_definition/dry_wet_bulb.html, [17.4.2024.]
- [50] Baaghdeh, M., Mayvaneh, F., Shojaei, T.: Evaluation of human thermal comfort using UTCI index: Case study Khorasan Razavi, *Natural Environment Change*, 2 (2016), pp. 165-175
- [51] Cost Action 730: Towards a Universal Thermal Climate Index (UTCI) for assessing the thermal environment of the human being, <https://www.cost.eu/actions/730/>, [1.3.2024.]
- [52] Blazejczyk, K., Epstein, Y., Jendritzky, G., Staiger, H., Tinz, B.: Comparison of UTCI to selected thermal indices, *International Journal of Biometeorology*, 56 (2012), pp. 515-535
- [53] Blazejczyk, K.: New climatological-and-physiological model of the human heat balance outdoor (MENEX) and its applications in bioclimatological studies in different scales, (1994) 1, pp. 27-58
- [54] Bedra, K.B., Zheng, J., Li, J., Sun, Z., Zheng, B.: Automating microclimate evaluation and optimization, *Sustainability*, 15 (2023).
- [55] Roudsari, M., Pak, M., Smith, A.: Ladybug: A parametric environmental plugin for Grasshopper to help designers create an environmentally-conscious design, BS2013, 2013.
- [56] Fink, T., Koenig, R.: Integrated parametric urban design in Grasshopper / Rhinoceros 3D demonstrated on a Master Plan in Vienna, Data - city information modelling and gis, 3 (2023), pp. 313-322
- [57] Weather Data, Energy Plus: <https://energyplus.net/weather>, [17.2.2024.]
- [58] Ladybug Tools LLC: What is Ladybug Tools?, <https://www.ladybug.tools/#intro>, [17.2.2024.]
- [59] Honeybee, Ladybug Tools LLC, <https://www.ladybug.tools/honeybee.html>, [17.2.2024.]
- [60] Ji, W., Yingxin, Z., Heng, D., Cao, B., Zhiwei, L., Yang, G., Shuli, L., Jianyin, X., Changhui, Y.: Interpretation of standard effective temperature (SET) and explorations on its modification and development, *Building and Environment*, 210 (2022).
- [61] Gagge, A., Fobelets, A., Berglund, L.: A standard predictive index of human response to the thermal environment, *ASHRAE Transactions*, 1986.
- [62] Elrefai, R., Nikolopoulou, M.: A simplified outdoor shading assessment method (OSAM) to identify outdoor shading requirements over the year within an urban context, *Sustainable Cities and Society*, 97 (2023).
- [63] Thermal Comfort Indices - Universal Thermal Climate Index, 1979-2020, Climate-ADAPT, <https://climate-adapt.eea.europa.eu/en/metadata/indicators/thermal-comfort-indices-universal-thermal-climate-index-1979-2019>, [14.5.2024.]
- [64] American Society of Heating, Refrigerating and Air-Conditioning Engineers: ANSI/ASHRAE Standard 55 Thermal Environmental Conditions for Human Occupancy, 2023.
- [65] Roussac, A.C., Bright, S.: Improving environmental performance through innovative commercial leasing: An Australian case study. *International Journal of Law in the Built Environment*, 4 (2012), pp. 6-22
- [66] Hancock, P.A., Ross, J.M., Szalma, J.L.: A meta-analysis of performance response under thermal stressors, *Humans Factors*, 49 (2007), pp. 851-877
- [67] Zhang, F., de Dear, R.: University students' cognitive performance under temperature cycles induced by direct load control events, *Indoor Air*, 27 (2016), pp. 78-93
- [68] Hardy, A., Mitchell, H.: Building a climate: The Wallsend project, Electricity Council, 1969.
- [69] Legg, R.: Air Conditioning System Design, Chapter 5 - Room Heat Gains, Air Diffusion, and Air Flow Rates, Elsevier Ltd., 2017.