Applied Engineering Letters **Vol.8, No.3, 101-110 (2023)** **e-ISSN: 2466-4847**

BUILDING DENSITY IMPACT ON FINAL ENERGY CONSUMPTION FOR ARTIFICIAL AND AUTOMATIC LIGHTING CONTROL SYSTEM IN THE SPORTS HALL – NUMERICAL CASE STUDY ANALYSIS

UDC:628.93:519.6
Original scientific paper
https://doi.org/10.18485/aeletters.2023.8.3.2

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Abstract:
An increasing number of new buildings equipped with modern and energy-efficient thermo-technical systems contribute to society's efforts to make urban environments more sustainable shortly than they were before. Despite this, the applied methods have negative consequences that slow down this process. On the (concrete) example of the sports hall, by analyzing the consumption of final (electrical) energy for artificial lightning, this paper pointed out the negative effects of shading in buildings – phenomena that arise as a consequence of accelerated urbanization, without more detailed planning prediction bases. To create this numerical study, the software packages EnergyPlus and Google SketchUp were used, which communicate via the Legacy OpenStudio platform. Based on the conducted simulations, it was concluded that the consumption of final (electrical) energy for artificial lighting can be increased over 2.59 times, depending on the next parameters: the shape factor and orientation of the building, technical characteristics of lighting, and windows, spatial planning and urbanization, etc. For the sake of creating sustainable cities, energy-eco projects should not focus only on individual buildings in the future, i.e. isolated cases. The problem should be looked at more broadly, taking into account at least the immediate environment, i.e. "communication" of the analyzed building with its surroundings.

ARTICLE HISTORY
Received: 6 March 2023
Revised: 24 June 2023
Accepted: 11 August 2023
Published: 30 September 2023

KEYWORDS
Artificial lighting, automatic lighting, building density, control systems, EnergyPlus software, final energy consumption, Numerical analysis

1. INTRODUCTION

According to IEA data [1], the residential sector accounts for 26.61%, and the commercial (with the public) sector account for 21.26% of global electricity consumption (Fig. 1). For artificial lighting, the residential sector consumes 10-15%, while the commercial (with the public) sector consumes 18-40% [2, 3]. In addition, global energy demand in the residential, commercial, and public sectors is expected to increase from 2020 to 2050. For this reason, future strategies for the sustainable development of countries, regions, and cities will pay special attention to energy consumption in buildings.

To reduce the consumption of final (electrical) energy for the needs of artificial lighting in the mentioned sectors (while maintaining comfort conditions), the literature has proposed a range of measures with building shading effects based on daylight illuminance control.

Different types of shading of vertical transparent surfaces on the external Facade of a building are presented in [4], while in [5] there is a review of simulation modeling for shading devices in buildings. Active shading systems (building

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applications, opportunities, and challenges) are presented in [6]. The most used lighting control functions and their implications on user comfort and energy load in different climate zones are compared in [7]. A major scientific contribution to this topic was made by an international study [8] which sublimates the evaluation of integrated daylighting and electric lighting design projects.

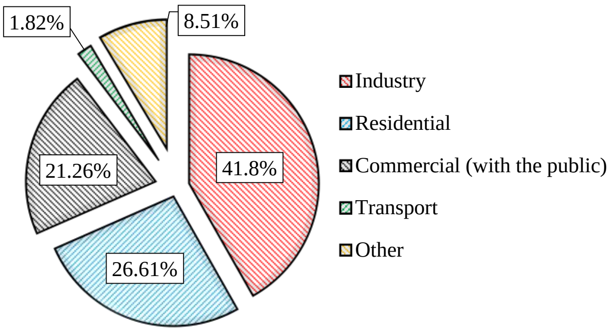

Fig. 1. Global electricity consumption by sectors in 2019

A specific lighting controller in a smart building system is investigated by Guillemin and Morel [9]. The control device worked in a double mode: visual comfort (when people stay in the building) and thermal comfort (when people don't stay in the building).

To minimize final energy consumption, dynamic numerical programming with the mutual interaction of thermo-technical systems (active and passive heating, cooling, lighting, shading, and ventilation systems) is presented in [10]. The study showed that such management strategies for HVAC lighting and shading systems reduce final energy consumption while improving human comfort.

Model predictive control for working the thermo-technical system with an innovative lighting system and shading control was developed by Yang et al. [11].

Tzempelikos and Athienitis in their study in [12], among other things, pointed out that shading provision should be considered as an integral part of fenestration system design for commercial and office buildings, to balance daylighting requirements versus the need to reduce solar gains.

Shan used TRNSIS software to simulate the thermal performance of a concrete office Facade, equipped with HVAC, and lighting systems, in order to minimize annual costs [13]. The results showed that the developed genetic algorithm can save time when searching for an optimal solution and that it could find application in architecture in the initial design phase.

The relationship between the lighting system and the occupant (on the one hand) and the shading system and the occupant (on the other hand) was investigated by Ding et al. [14].

The office building was the subject of study by Xie and Sawyer [15], the fact that they used a data-driven method for glare control with automated shading systems in their research.

Bayram and Kazanasmaz, with their simulation research [16], drew attention to the importance of carefully designing shading devices in academic buildings to maximize the use of daylight, that is, to minimize the use of daylight and electricity.

Sun et al. also investigated (numerically) the effects of building-sun-shading design on lighting and ventilation in teaching buildings [17].

Heydarzadeh et al. presented in [18] a method by which the consumption of final energy for cooling in a modern office building in the territory of the city of Tehran can be reduced by 14.86%, while at the same time better utilization of daylight (by 20.04%).

The shading effect in the mentioned works is seen as an internal factor that is positive for the end user because it can be controlled. On the other hand, there are external shading effects that cannot be controlled by the user, and which have a bad effect on the energy-eco performance (for example, on the operation of the PV system [19]) of the analyzed building. They are characteristic of urban environments and are created by the uncontrolled construction of new (higher) buildings near existing ones.

Numerical simulation of daylighting, electric lighting, heating, and cooling for office applications (on an annual basis), using modern software tools [20], was carried out by Safranek and Abboushi.

In terms of energy, Krarti [21] evaluated the benefits of using dynamic sliding external curtains for transparent elements, in both existing and newer buildings.

To find a compromise between interior comfort, operational energy, and environmental costs, Pinto et al. proposed a specific and innovative methodological approach for the control of solar shading devices using the example of a commercial building in Italy [22].

A quantitative method for analyzing the use of natural (daylight) light in the morning, afternoon, and evening hours in an office building is presented in [23].

Detailed theoretical analysis of energy consumption for artificial lighting and HVAC system based on thermo-optical analysis is given in [24].

According to the results reached by Dev and Saifudeen in [25], the dynamic facade offers a compromise (optimal solution) between internal (artificial) lighting and natural light.

Sarmadi and Mahdavinejad in their study presented in [26] first drew attention to the improper use of single and double windows in practice. Then they developed three simulation scenarios (all-algae, all-glass, and combined glass and microalgae.) to come up with patterns (algorithms) that would ensure the design of facades with optimal control of daylight glare, with quality use of the ventilation system. The results showed that combined facades (with a concentration of microalgae 50-60%) achieve the best design patterns.

Due to all of the above, the author in this paper uses numerical analysis (using the EnergyPlus and Google SketchUp software) to show, in the concrete example of a sports hall, that in some cases, with an increase in building density, the use of energy-efficient systems (such as artificial and automatic lighting) cannot achieve benefits for the end user.

2. MATERIALS AND METHODS

2.1 Building description

The research subject is the sports hall shown in (Fig. 2).

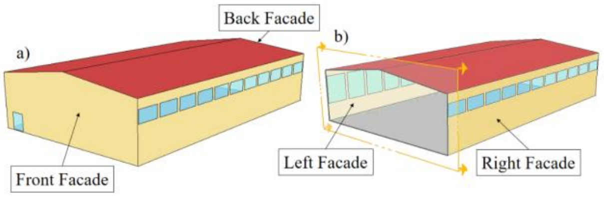

Fig. 2. Sports hall isometric view
a) External appearance; b) Internal appearance

The net area and net volume of the analyzed building are respectively: 1130.04 m^2 (base dimensions 43.8×25.8 m) and 10396.37 m^3 (maximum, average, and minimum height, respectively: 10 m, 9.2 m, and 8.4 m). The total area of the thermal envelope is 3479.3 m^2. The main entrance (external door measuring 2.2×2.6 m) is located on the front Facade wall (Fig. 2a). There is another door at the backside. On the right Facade wall (Fig. 2b) 11 identical windows are measuring 3.5×1.8 m, while on the left Facade wall (Fig. 2b) all windows (also 11 of them) measure 3.5×4.5 m. All transparent surfaces have identical thermal characteristics (Table 1).

Table 1. Glass thermal characteristics

Parameter	Unit	Value
Thickness	mm	3
Conductivity	W/mK	0.9
Solar transmittance at normal incident	-	0.837
Solar reflectance at normal incident	-	0.075
Visible transmittance at normal incident	-	0.898
Visible reflectance at normal incident	-	0.081
Infrared transmittance at normal incidence	-	0
Infrared hemispherical emissivity	-	0.84

The height of the right and left parapets are 5.25 m, and 2.85 m, respectively. The window-wall ratio is 20.98%, while the form factor (ratio of the total area of the thermal envelope and the net storage building) of the sports hall is 0.33.

2.2 Suspended lights description

For this study, of the thermo-technical systems, only artificial lighting was implemented in the sports hall. These are suspended lights (Fig. 3, Table 2) with a total output power of 5700 W (5.04 W/m^2).

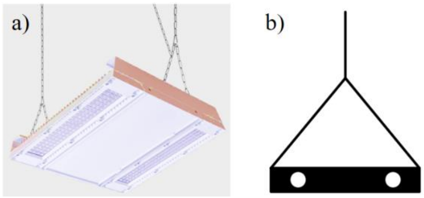

Fig. 3. Suspended lights
a) Isometric view; b) EnergyPlus symbol

Table 2. Glass thermal characteristics

Parameter	Symbol	Unit	Value
One suspended light nominal electric power	-	W	100
Suspended lights number	-	-	57
Return air fraction	RAF	-	0
Fraction radiant	FR	-	0.42
Fraction visible	FV	-	0.18
Convective heat gains	CHG	-	0.4

For example (Table 2), suspended lights, compared to surface mount lights, are characterized by a lower value of FR, and thus a higher value of CHG (both for 0.3), because the sum of FR, FV, and CHG must be 1, i.e. 100%.

To provide the best illumination of the sports hall, suspended lights are arranged in 5 rows (Fig. 4).

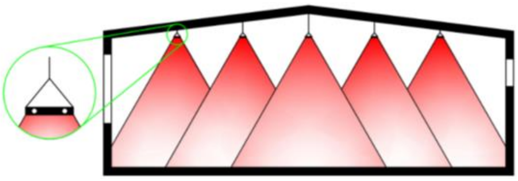

Fig. 4. Suspended lights disposition

2.3 EnergyPlus software

The EnergyPlus software is a relatively useful tool for modeling building energy and environmental behavior. This was accomplished by using many integrated mathematical models that simulate the operation of various thermo-technical systems, including artificial and automatic lighting control systems. The software package was initially developed by Lawrence Berkeley National Laboratory, the U.S. Army Construction Engineering Laboratory, and the University of Illinois.

2.4 Google SketchUp software

The Google SketchUp software is intended for 3D modeling. The software is intended to be as flexible and easy to use as possible other CAD programs for 3D computer design.

Google SketchUp has more features: tools for basic and special 3D editing, the possibility of working with scenes, styles support, quick creation of three-dimensional text, integration with the Google Earth service, the possibility of working with ready-made models, and support of popular 3D graphics formats.

Communication between Google SketchUp software and EnergyPlus software is enabled by the specially designed Legacy OpenStudio platform.

3. METHODS

3.1 Automatic lighting control system

The automatic lighting control system is based on a method that calculates daylighting illuminance to determine how much electric lighting can be reduced.

The reduction of electric lighting depends on the next indicators: (1) daylight illuminance level, (2) illuminance set point position in the analyzed building (Fig. 5), (3) the fraction of zone controlled (Steps number equal to the number of the suspended light, Table 2), and (4) type of lighting control (stepped control).

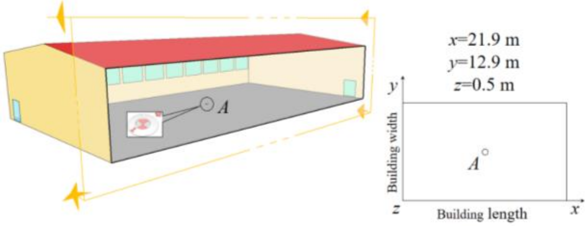

Fig. 5. Illuminance set point design and position in the sports hall

The daylight illuminance level in a zone depends on many factors, including size, and glass transmittance of windows (Table 1), location parameters (Table 3), sky condition, Sun position, window shading devices, and reflectance of interior surfaces.

3.2 Location parameters

The City of Kragujevac (the latitude of 44.02°N, the longitude of 20.92°E) is situated on the banks of the Lepenica River, at an altitude of 209 m, in the time zone of GMT+1 h.

Table 3. Meteorological data for Kragujevac

Month / Parameter	Air temperature	Diffuse solar radiation	Beam solar radiation
Unit	°C	kWh/m^2	kWh/m^2
Jan	-0.24	33.30	63.63
Feb	0.88	49.39	86.66
Mar	5.57	77.08	106.12
Apr	10.87	92.65	149.02
May	16.06	113.30	176.45
Jun	18.85	109.50	208.94
Jul	20.78	110.60	228.12
Aug	20.38	96.25	215.40
Sep	16.68	75.54	166.92
Oct	11.18	57.34	119.43
Nov	6.08	39.83	64.51
Dec	1.13	28.66	58.86

The climate (Table 3) is moderately continental, with pronounced seasons. The summers are hot and humid, with temperatures reaching 37°C.

On the other hand, the winters are cold (with temperatures going below -12°C) and with snow.

3.3 Simulation scenario

In the first part of the numerical analysis (using the EnergyPlus software), the optimal position of the sports hall in space is determined by rotating its left Facade (with larger windows, Fig. 2b) in the direction of North (Fig. 6a), South (Fig. 6b), West (Fig. 6c) and East (Fig. 6d).

The optimal position of the analyzed geometry should maximize the use of daylight, that is, minimize the consumption of final (electrical) energy for artificial and automatic lighting. Within this phase, the application of single-layer (Fig. 6e), double-layer (Fig. 6f), and three-layer (Fig. 6g) transparent surfaces is examined.

In the central part of the work, three scenarios (Figs. 7-9) of an optimally oriented sports hall, when there are one or two buildings (with 8 floors, height 20.8 m) in its vicinity, were elaborated.

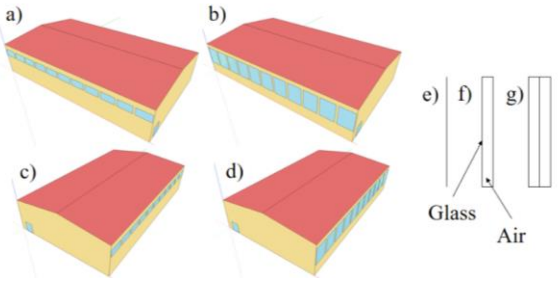

Fig. 6. Left Facade orientation of the sports hall:
a) North; b) South; c) West; d) East;
e) Single-layer glass; f) Double-layer glass; g) Three-layer glass

In the first (S1) scenario, the neighboring eight-story building, the so-called "shadow source", obscures the right Facade of the sports hall (Fig. 7).

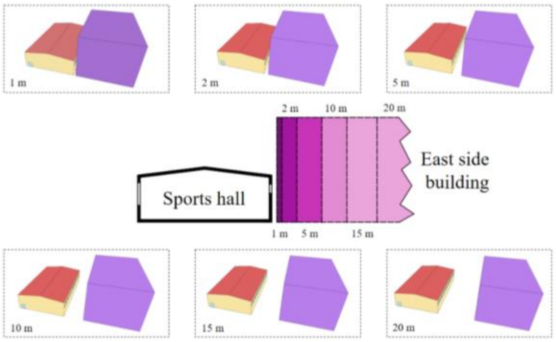

Fig. 7. Sports hall shading effect (the adjacent building on the right)

In the second (S2) scenario, it obscures the left Facade of the sports hall (Fig. 8). In the third (S3) scenario, the effects of double-sided shading of the sports hall are examined, which arise in the case of building construction, both on the right and the left Facade (Fig. 8). In other words, scenario S3 is a combination of scenarios S1 and S2.

In all simulation scenarios, one more variable is taken into account, which is the distance between the neighboring building (Fig. 7, Fig. 8), i.e. neighboring buildings (Fig. 9), and the sports hall: 1 m, 2 m, 5 m, 10 m, 15 m, and 20 m.

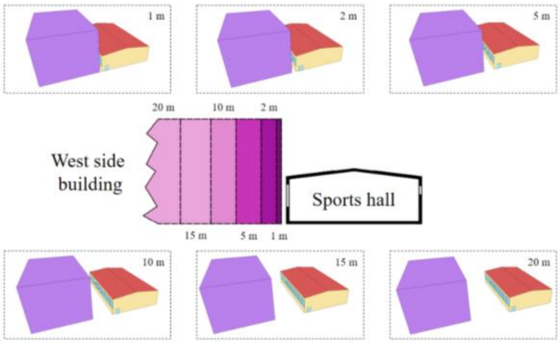

Fig. 8. Sports hall shading effect (the adjacent building on the left)

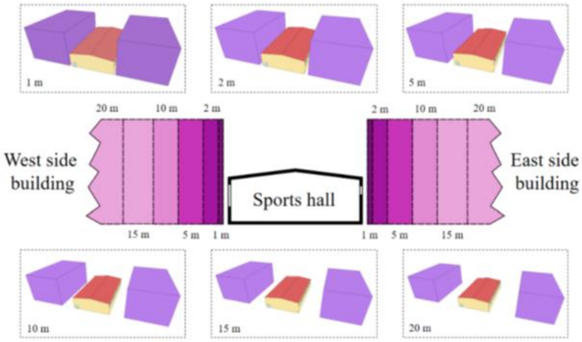

Fig. 9. Sports hall shading effect (adjacent buildings on the left and right)

The calculations and analysis are made for every day of the week (all year) from 08:00 to 22:00 h, which is presented the annual specific electricity consumption for artificial and automatic lighting in the sports hall.

4. RESULTS AND DISCUSSION

Annual specific electricity consumption for artificial and automatic lighting in the sports hall depending on the orientation of the left Facade wall (with larger windows, Fig. 2b), and the layering of the windows, is shown in Fig. 10.

The first thing that can be seen from the diagram (Fig. 10) is that the daylight illuminance level in the sports hall decreases with increasing layers of glass in the window construction. Deficit daylight illuminance is compensated using artificial and automatic lighting, i.e. by an additional investment of electricity. On the other hand, the investment of electrical energy for artificial and automatic lighting can be reduced, if the orientation of the analyzed building (in this case the sports hall) is taken into account in the design phase, by its building physics (Fig. 10).

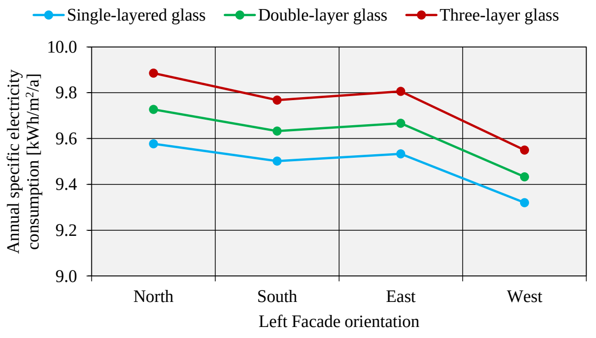

Fig. 10. Annual specific electricity consumption for artificial and automatic lighting in the sports hall depending on the left Facade orientation and glass layers

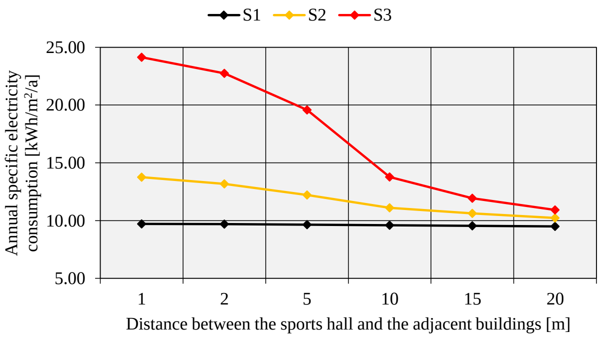

Fig. 11. Annual specific electricity consumption for artificial and automatic lighting in the sports hall depending on the scenario simulation and distance between the sports hall and the adjacent buildings

As 47.09% of the left Facade is glazed, and the right Facade much less (18.84%), the annual specific consumption of electricity for artificial and automatic lighting in the sports hall is the lowest when the left Facade is oriented to the West, and the right to the East (Fig. 10): 9.32 $kWh/m^2/a$ (for single-layer glass), 9.43 $kWh/m^2/a$ (for double-layer glass), and 9.55 $kWh/m^2/a$ (for three-layer glass). The most unfavorable case is that the left Facade is oriented to the North, and the right to the South (Fig. 10): 9.58 $kWh/m^2/a$ (for single-layer glass), 9.73 $kWh/m^2/a$ (for double-layer glass), and 9.89 $kWh/m^2/a$ (for three-layer glass). In other words, in the case of the Western orientation of the left Facade, the following savings can be achieved about its Northern orientation (Fig. 10): 2.75% (for single-layer glass), 3.12% (for double-layer glass), and 3.52% (for three-layer glass).

Interesting results are obtained by exposing the left Facade to the South (the right Facade is exposed to the North). Or to the East (the right Facade is exposed to the West). Namely, then similar results are obtained, with the fact that the Southern orientation of the left Facade gives a slight advantage in terms of using daylight illuminance (Fig. 10): single-layer (9.5 $kWh/m^2/a$ – South orientation, 9.53 $kWh/m^2/a$ – East orientation), double-layer (9.63 $kWh/m^2/a$ – South orientation, 9.67 $kWh/m^2/a$ – East orientation), and three-layer (9.77 $kWh/m^2/a$ – South orientation, 9.81 $kWh/m^2/a$ – East orientation).

Annual specific consumption of electricity for artificial and automatic lighting in the sports hall, for East (right Facade) – West (left Facade) orientation, depending on the number and position of neighboring buildings (S1, S2, and S3), and their distances (1 m, 2 m, 5 m, 10 m, 15 m, and 20 m) from the analyzed building, is shown in Fig. 11.

In the case of scenario S1 (Fig. 7), the annual specific electricity consumption for artificial and automatic lighting in the sports hall has a slightly decreasing trend as the neighboring building moves away from the sports hall: 9.72 $kWh/m^2/a$ (for 1 m), 9.7 $kWh/m^2/a$ (for 2 m), 9.65 $kWh/m^2/a$ (for 5 m), 9.59 $kWh/m^2/a$ (for 10 m), 9.54 $kWh/m^2/a$ (for 15 m), and 9.5 $kWh/m^2/a$ (for 20 m). About the sports hall with the same orientation, but without the shadowing effect (left Facade west, single-layer glass, Fig. 10), the consumption of electricity can be increased by 1.94% (for 20 m), i.e. by 4.26% (for 1 m).

Scenario S2 is an even more unfavorable case for the sports hall. By covering the Facade with 173.25 m^2 of transparent surfaces (Fig. 2, Fig. 8), the annual specific consumption of electricity for artificial and automatic lighting in the sports hall can reach the value of 13.75 $kWh/m^2/a$ (for 1 m). The diagram (Fig. 11) also shows that the differences between scenarios S1 and S2 decrease as the distance between the neighboring building and the sports hall increases: by 4.04 $kWh/m^2/a$ consumption in scenario S2 is higher than in scenario S1 (for 1 m), and by 0.73 $kWh/m^2/a$ consumption in scenario S2 is higher than in scenario S1 (for 20 m).

The sports hall in the case of double-sided shading (scenario S3) consumes the most electricity for artificial and automatic lighting (Fig. 11): 24.14 $kWh/m^2/a$ (for 1 m), 22.75 $kWh/m^2/a$ (for 2 m), 19.58 $kWh/m^2/a$ (for 5 m), 13.77 $kWh/m^2/a$ (for 10 m), 11.93 $kWh/m^2/a$ (for 15 m), and 10.93 $kWh/m^2/a$ (for 20 m). In these circumstances, the position of the construction line on the neighboring plots is very important, because the consumption of electricity for the needs of artificial lighting can increase up to 1.76 times (compared to S2), 2.48 times (compared to

S1), and 2.59 times (compared to the sports hall without neighboring buildings), if the neighboring buildings are located at a distance of 1 m from the sports hall.

The following pictures (Figs. 12-17) show the daily fluctuations of the electricity for artificial and automatic lighting in the sports hall, for two characteristic days during the year: the summer-long day (Figs. 12-14) and the winter-short day (Figs. 15-17).

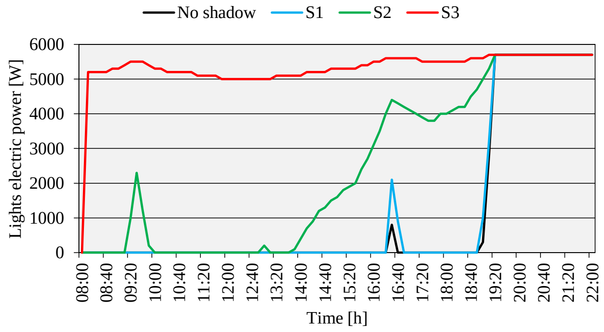

Fig. 12. Lights electric power depending on the scenario simulation during June 21 (distance between the sports hall and the adjacent buildings are 1 m)

The average daily use of electric lighting in the sports hall, during June 21 (summer solstice), for different cases of shading, when the distance between buildings is 1 m, is (Fig. 12): 1185.88 W (without shading), 1224.71 W (scenario S1), 2392.94 W (scenario S2), and 5321.18 W (scenario S3). For example, for the same day, same shading conditions, but for a distance of 5 m, the results are as follows (Fig. 13): 1221.18 W (scenario S1), 2143.53 W (scenario S2), and 4372.94 W (scenario S3). The best results are achieved when the distance is the greatest, i.e. in this case 20 m (Fig. 14): 1207.06 W (scenario S1), 1530.59 W (scenario S2), and 1787.06 W (scenario S3).

In Figs. 12-14, one can see a discontinuity on the "no shading" curve in the period 16:20-16:40 h, which is reflected in all analyzed cases. This phenomenon that 8/57 lights (a total of 800 W) are engaged during the summer-long days in the mentioned period can be explained by unfavorable weather conditions, i.e. due to the presence of clouds, due to which less daylight illuminance reaches the sports hall.

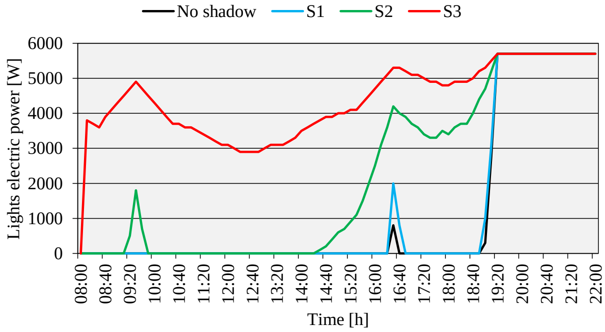

Fig. 13. Lights electric power depending on the scenario simulation during June 21 (distance between the sports hall and the adjacent buildings are 5 m)

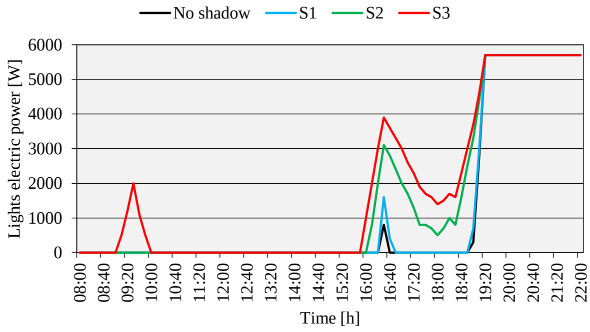

Fig. 14. Lights electric power depending on the scenario simulation during June 21 (distance between the sports hall and the adjacent buildings are 20 m)

December 21, the day of the year is the shortest, so that is when the light's electric power is the highest. In the case of the minimum distance (1 m), the average daily use of electric lighting is (Fig. 15): 2757.65 W (without shading), 3031.76 W (scenario S1), 4162.35 W (scenario S2), and 5511.76 W (scenario S3). If the distance is increased to 5 m, the results are more favorable for the sports hall (Fig. 16): 3001.18 W (scenario S1), 3704.71 W (scenario S2), and 4827.06 W (scenario S3).

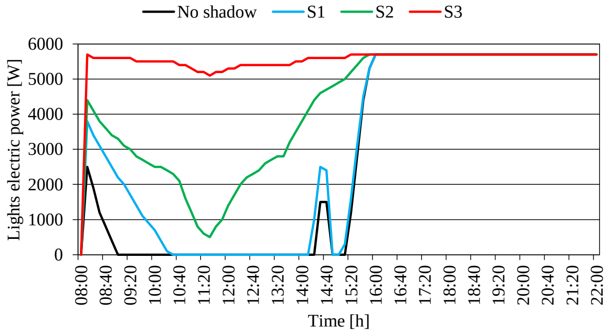

Fig. 15. Lights electric power depending on the scenario simulation during December 21 (distance between the sports hall and the adjacent buildings are 1 m)

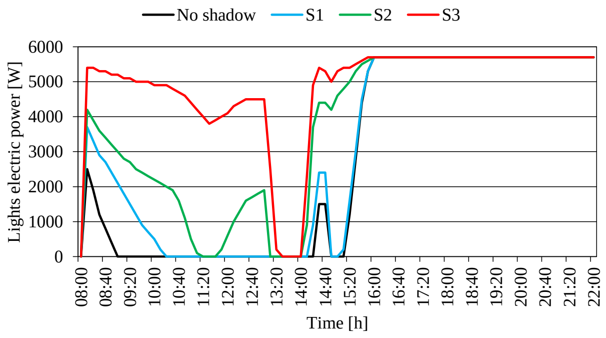

Fig. 16. Lights electric power depending on the scenario simulation during December 21 (distance between the sports hall and the adjacent buildings are 5 m)

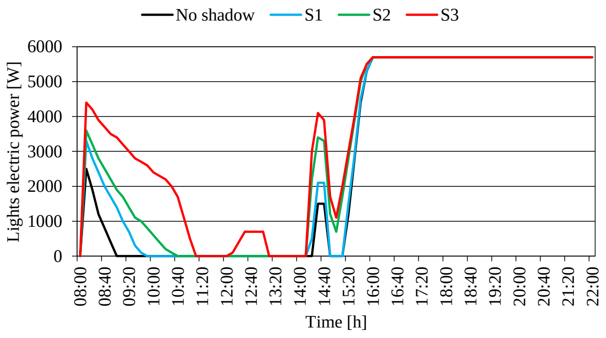

Fig. 17. Lights electric power depending on the scenario simulation during December 21 (distance between the sports hall and the adjacent buildings are 20 m)

In the end, a distance of 20 m brings the greatest benefits per sports hall (Fig. 17): 2888.24 W (scenario S1), 3107.06 W (scenario S2), and 3496.47 W (scenario S3).

5. CONCLUSION

Accelerated development of urban areas, i.e. of larger cities in Serbia, often does not follow spatial planning, urban parameters for achieving energy efficiency, city infrastructure, and other important elements of preserving the quality of life of citizens and the environment.

Through numerical research, using EnergyPlus and Google SketchUp software, on the specific example of the sports hall, the authors tried to draw attention to the mentioned negative effects, which slow down the desired goal, which is the achievement of sustainable development.

The sports hall is equipped with a large number of windows and a modern automatic lighting system, to reduce the consumption of final (electrical) energy, reduce the emission of greenhouse gases, and protect the environment.

The mentioned system makes sense to use only if it is taken into account during spatial planning and if the density of construction on neighboring plots is taken into account. Otherwise, the annual consumption of electricity, just for the needs of lighting, in the sports hall, increases from 10532.27 kWh/a to 27279.85 kWh/a, and realistically even more than that, all depending on the number of buildings, their mutual distance, and their stories. In other words, in some situations, the effect can be reached that the application of automatic lighting does not make any sense, i.e. the advantage of using it compared to classic lighting without any control system.

Designers, engineers, architects, and others take into account the energy efficiency of thermo-technical systems in the building itself, high-quality construction materials, and other internal parameters. Still, one gets the impression that external influencing parameters, both natural and artificial, are often neglected, although sustainable cities cannot be imagined without them.

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