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# Multi-criterion optimization of building envelope in the function of indoor illumination quality towards overall energy performance improvement

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ABSTRACT

This paper elaborates the formulation and application of an integral methodology for overall energy performance improvement of office buildings and demonstrates its application. The developed multi-objective methodology is demonstrated on a reference office building located in a temperate climate zone with high annual temperature variations. The idea is to formulate a research based proposition in building science with a formulation of a general/integral methodology which could be applied widely in energy performance refurbishment of existing office buildings and help architects and engineers in the early-design stages of new projects. The goal was to formulate an optimized building envelope model using multi-criterion optimization methodology in order to determine efficient window to wall ratio (WWR) and window geometry (WG) in the function of indoor illumination quality, followed by the assessment of glazing parameters influence on the annual energy demand. The integral methodology for overall energy performance improvement of office buildings utilizes multi-criterion optimization method and highly detailed Building Information Modeling (BIM) programs and dynamic energy simulation engines. The developed coupled-integral methodology links together both building envelope construction optimization and user comfort. The methodology is both flexible and adaptable for application in various climatic conditions and for different construction types.



## 1. Introduction

According to the International Energy Agency (IEA), buildings exceed 40% of world energy demand and emit close to 1/3 of $CO_2$ worldwide [1]. The need to optimize building energy performance was elaborated in numerous researches using various analysis methods, energy simulations and techniques in order to design sustainable, energy efficient and cost-effective buildings [2–7]. Authors Eui-Jong et al. developed a simplified model of building envelope design using physically simplified city simulation tools [8]. Rahman elaborated the energy and environmental life cycle assessment of office building envelopes [9]. Authors Attia et al. have summarized potential challenges and opportunities for integrating simulation-based building performance optimization tools in net zero energy buildings design [10].

Illumination performance analysis has been a widespread topic investigated in numerous papers via simplified models, daylight coefficient concept, daylighting schemes, window properties, building design and climate conditions [11–15]. Building simulation for energy strategy formulation in façade retrofitting different climatic conditions of EU was investigated by authors Capeulo and Ochoa [16]. A detailed multi-level optimization principle was demonstrated by Evins in a process on a straight-forward test case, applied to a case study simplified office building [17].

Thermal and lighting simulations applying energy modeling, glazing's transmittance dependence and envelope thickness and economic aspects were investigated in previous researches [18–21].

A recently published investigation from authors Ma et al. [22] investigated window to wall ratio as a function of two parameters; U-value and ambient temperature amplitude. Authors stated that factors which are heat gain related such as solar heat gain coefficient (SHGC), shading, sky cloudiness and building

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orientation do have a great impact on window to wall ratio (WWR) determination; however it was impossible to consider. Thus the authors propose the assumption of these factors. However, the multi-criterion optimization methodology applied in our research elaborates building envelope, window to wall ratio and window geometry selection further, by implementing various factors in the optimization process which influence indoor illumination quality, electricity reduction for lighting and exterior glazing properties in the aim of overall energy performance improvement of existing or newly designed office buildings.

This paper elaborates the formulation and application of an integral methodology for overall energy performance improvement of office buildings and demonstrates its application on an existing reference building. The idea is to formulate a general/integral methodology which could be applied widely in energy performance refurbishment of existing buildings and help architects and engineers in the early-design stages of new projects.

The developed coupled-integral methodology links together both building envelope construction optimization and user comfort. It is flexible and adaptable for application in various climatic conditions and for different building energy efficiency directives and regulations. The development process of the multi-objective methodology consisted of four major phases, which can be seen in the flowchart, Fig. 1. The first three phases refer to data analysis and construction of the reference building's computational model. In the first phase technical data, construction and building material data, HVAC data, and monthly energy expenses where gathered. Building's district heating energy utilization was monitored respectively. The second phase referred to the detailed processing, analysis and evaluation of the gathered data packages. Building performance was evaluated and critical building operation errors were determined. Finally in the third phase a computational CAD model was created using Building Information Modeling (BIM) technology where building geometry, function, construction and material data were integrated. Following the computational model's construction the multi-criterion optimization in the fourth phase referred to the determination of adequate window to wall ratio (WWR) and window geometry (WG) in the function of visual comfort and predefined parameters. Afterwards the optimized Best Case Energy Performance Scenario was determined according to glazing parameters and climate data using dynamic energy performance simulation.

The integral methodology will be demonstrated on a reference office building model located in a temperate climate zone with high annual temperature variations.

In order to formulate an efficient solution for building envelope improvement according to the European Standards, EN 15251 [23], the building was investigated as a dynamic multi-zone thermal system using multi-criterion research methodology. Building envelope performance is investigated both from glazing performance and thermal performance (heating and cooling demand) aspects by using multi-criterion optimization. Efficient WWR and WG was determined in the function of three criteria:

- Advanced spatial daylight dispersion analysis,
- Average daylight factor determination,
- Electric lighting reduction using automatic sensor system.

Authors Gvozdenac et al. elaborated the energy policy situation in Serbia and in the European Union [24–26], where authors determined that Serbia lags behind in the process of improving energy efficiency due to inadequate and slow institutional organization and application of state instruments in order to implement strategies.

The research was conducted on a typical not refurbished existing reference multi-level office building (total area 3430 m$^2$)

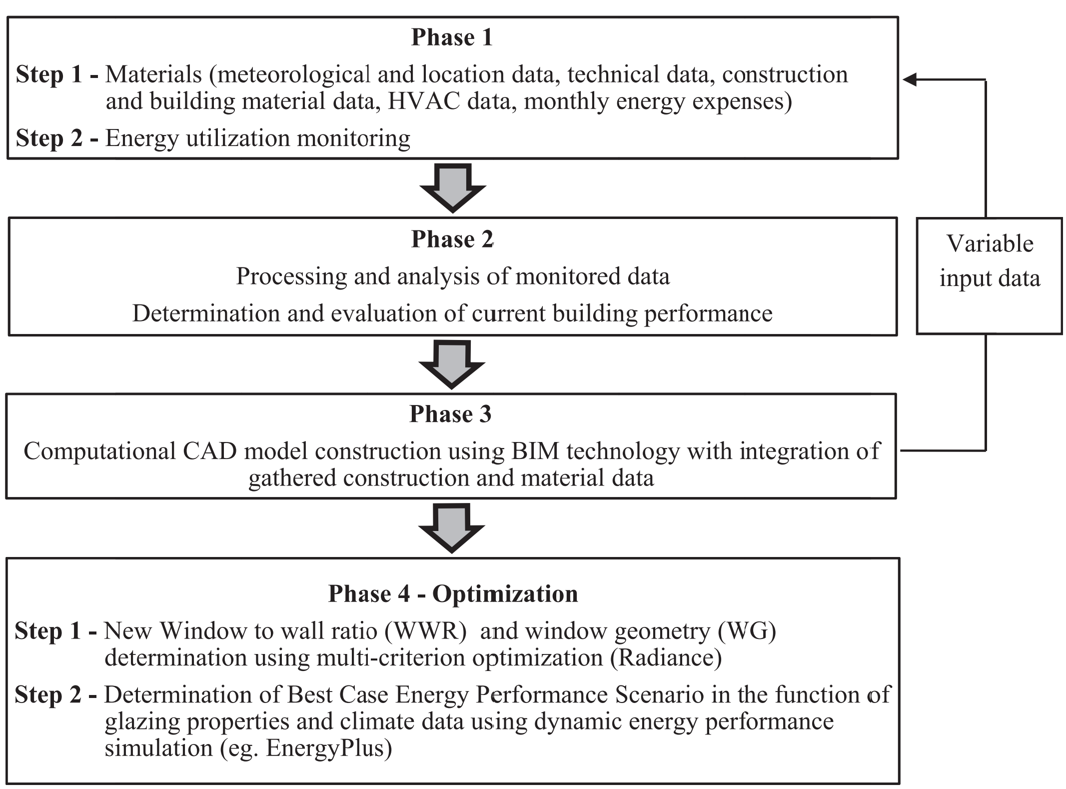



**Fig. 1.** Integral methodology flowchart.

located in the district of the University of Novi Sad in Serbia. The aim was to determine the heating and cooling energy demand in the function of building envelope properties (WWR, WG, glazing properties and exterior wall thermal properties) in order to offer effective methods for energy performance improvement.

The workflow consisted of the following three phases:

- Phase I; Multi-criterion optimization of building envelope.
- Phase II; Multi-zone thermal model construction and simulation data implementation.
- Phase III; Dynamic simulation of various scenarios in the function of glazing parameters.

## 2. Materials and methodology

### 2.1. Location and climate data

In phase 1, Location and climate data were imported from the global climatological database Meteonorm 7 [27]. The climate data package was converted into EnergyPlus Weather file (EPW) format in hourly intervals. Monthly average climate data from Meteonorm 7 database are shown in Table 1. Average monthly radiation energy and temperature oscillations are shown in Fig. 2.

In Table 2, the location and building situation are merged with an image of the reference office building. Annual sun path diagram and building orientation are presented in Fig. 3.

### 2.2. Energy utilization data and energy performance evaluation

In the first phase energy expenses for district heating and electricity were collected over the past three years, from 2011 to 2013, in order to analyze and evaluate the energy performance of the reference building, Figs. 4 and 5. During the gathered data analysis in the second phase it was concluded that hydraulic imbalance exists in the building's district heating systems. The delivered energy deviation to the floors was significant. The energy utilization for heating as seen in Fig. 4 was 442 MW h/a (128 kW h/m$^2$/a) in 2011, 338 MW h/a (98 kW h/m$^2$/a) in 2012, and 378 MW h/a (110 kW h/m$^2$/a) in 2013.

Monthly electricity utilization as seen in Fig. 5, in 2011 presented uniform expenses throughout the year between 16 and 20 MW h, while in 2012 and 2013 the total electricity utilization was between 14 and 21 MW h.

In Table 3 monthly heating energy expenses in 2013 are merged with average air temperature values from the Republic Hydrometeorology Service of Serbia, database for Novi Sad (Location in RS “Rimski Šančevi”) [28]. District heating was turned off over the period from the 15.04. to 15.10.2013. The highest heating demand was recorded in January, 34 kW h/m$^2$/mo., when the average outdoor temperature was 2.5 °C, yet during March only 12 kW h/m$^2$/mo. while the average outdoor temperature was 5 °C.

Unfortunately precise comparison of the energy expenses and the simulated values could not be compared precisely due to manual operation of the heating and cooling system, and ventilation. The determination of relational values among these loads were unknown:

- Precise occupancy schedules and intensity;
- Cooling system operation (operated manually);
- Cooling intensity (operated manually);
- Lighting schedules and intensity (operated manually);
- Electric equipment (operated manually).

### 2.3. Applied method for air-ventilation energy demand determination

The optimized Best Case Energy Performance Scenario's energy demand for air-ventilation was determined according to the European Standard EN 15251 “Annex B; Basis for the criteria for indoor air quality and ventilation rates; Recommended design ventilation rates in non-residential buildings” [29], the energy amount for air preparation was determined before entering the building's ventilation system. The total ventilation rate for the space was calculated by the following eq. (1):

$$q_{tot} = n \cdot q_p + A \cdot q_b \quad (1)$$

where:

$q_{tot}$ - Total ventilation rate of the room, [m$^3$/h]
$n$ - Design value for office occupancy, [−]
$q_p$ - Ventilation rate for occupancy per person, [m$^3$/h], pers.
$A$ - Room floor area, [m$^2$]
$q_b$ - Ventilation rate for emissions from building, [m$^3$/h], [m$^2$]

Ventilation rates can be adjusted according to the ventilation efficiency if the performance of air distribution differs from complete mixing, and can be reliably proven, EN 12521 [29]. In the calculations for single offices 7.0 l/s (25.2 m$^3$/h) per m$^2$ was adopted in the case of occupancy ($q_p$) and 0.7 l/s (2.52 m$^3$/h) per m$^2$ was adopted in the case of low polluted building ($q_b$).

The energy required for preparation of outdoor air which demands heating/cooling before entering the building was determined according to the following eq. (2) filtration heat demand

**Table 1**
Climate data — monthly average values for Novi Sad.

| Month | Air temp. | Global radiation | Relative humidity | Diffuse radiation | Wind speed | Sunshine duration | Snow depth |
|---|---|---|---|---|---|---|---|
| Jan | 0.4 | 46.3 | 81.9 | 26 | 2.6 | 70 | 5.2 |
| Feb | 2.3 | 84.5 | 76.8 | 41.1 | 2.8 | 89 | 0.8 |
| Mar | 7.3 | 137.7 | 65 | 60.5 | 3.1 | 145 | 2.7 |
| Apr | 12.7 | 191 | 62.7 | 93.5 | 2.9 | 180 | 0 |
| May | 18 | 241.8 | 63.3 | 105.5 | 2.4 | 230 | 0 |
| Jun | 20.8 | 258.8 | 65.9 | 118.4 | 2.1 | 251 | 0 |
| Jul | 22.4 | 268.5 | 64.2 | 100.2 | 2.1 | 289 | 0 |
| Aug | 22.2 | 226.8 | 63.3 | 98.3 | 1.9 | 269 | 0 |
| Sep | 16.9 | 161.5 | 68.6 | 77.1 | 2 | 207 | 0 |
| Oct | 12.6 | 107.5 | 73.6 | 58.8 | 2.3 | 170 | 0 |
| Nov | 7.1 | 63 | 78.7 | 35 | 2.6 | 87 | 0.4 |
| Dec | 1.7 | 38.7 | 83.8 | 23.2 | 2.6 | 60 | 15.2 |
| Year | 12 | 152.2 | 70.7 | 69.9 | 2.5 | 2047 | 2 |

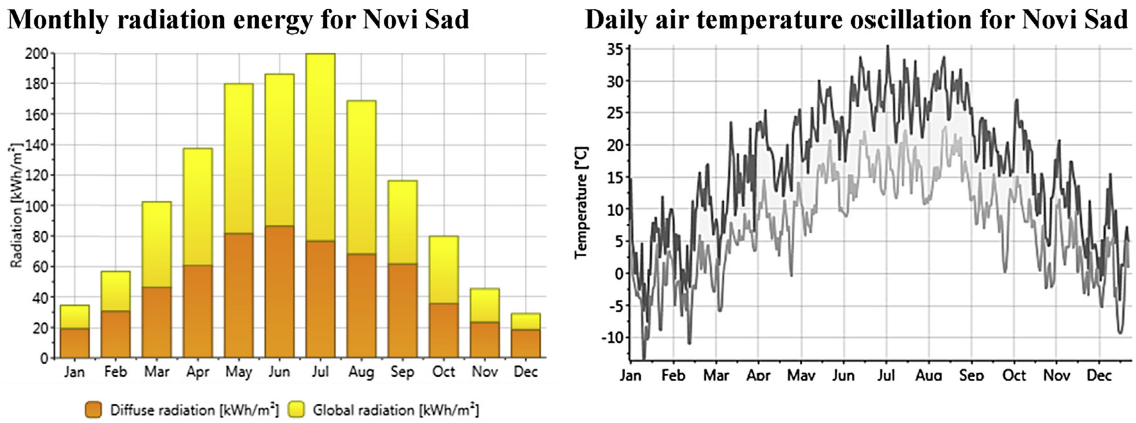
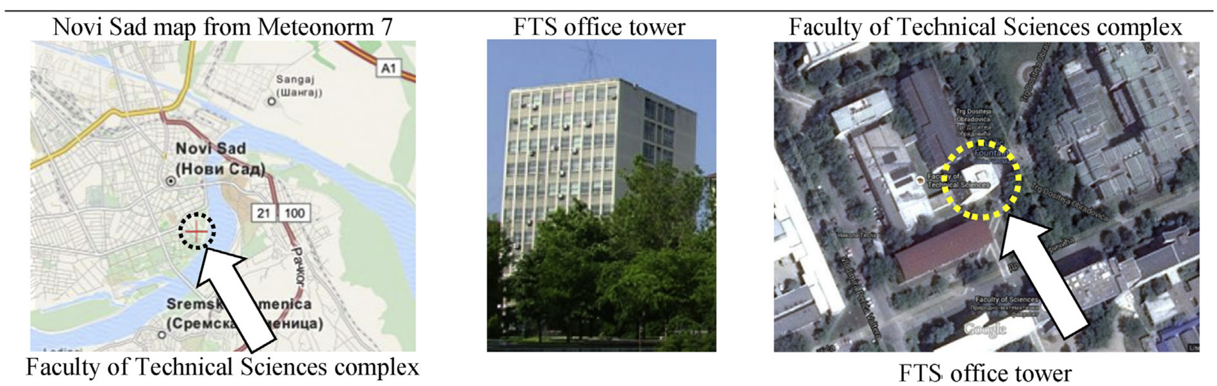



**Fig. 2.** Average radiation energy and temperature oscillations.

**Table 2**
Reference office building location.



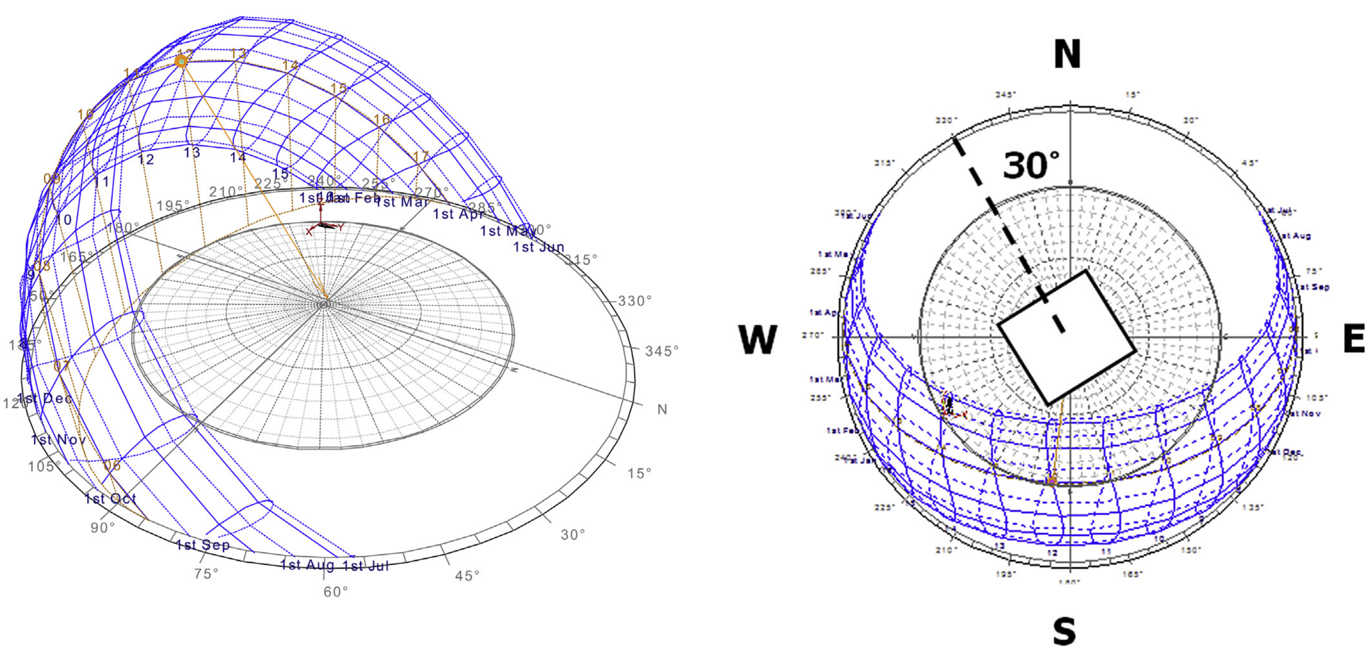




**Fig. 3.** Annual sun path and building orientation.

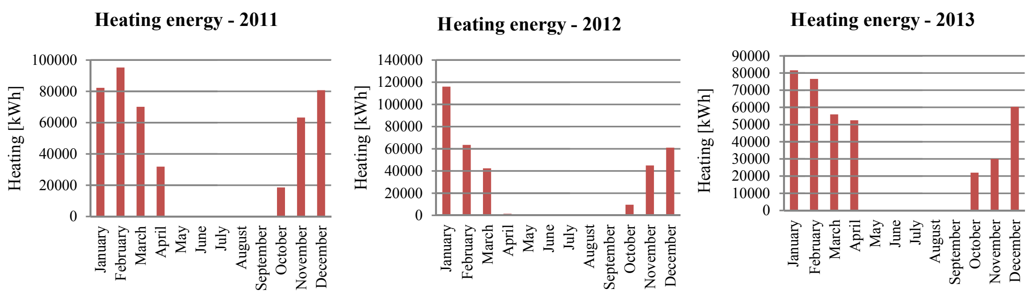



**Fig. 4.** District heating energy utilization for 2011, 2012 and 2013.

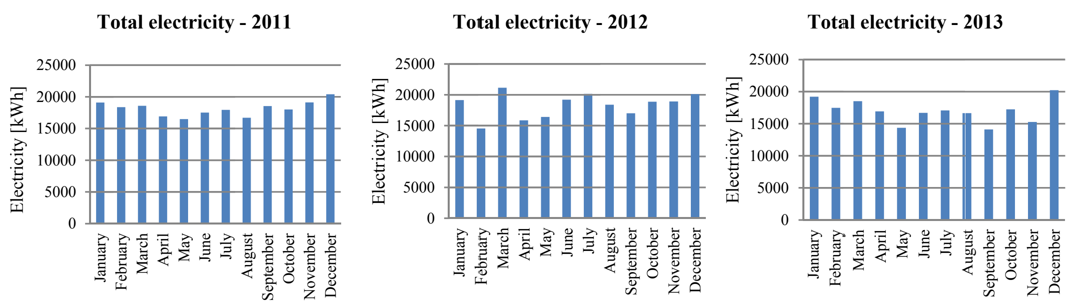
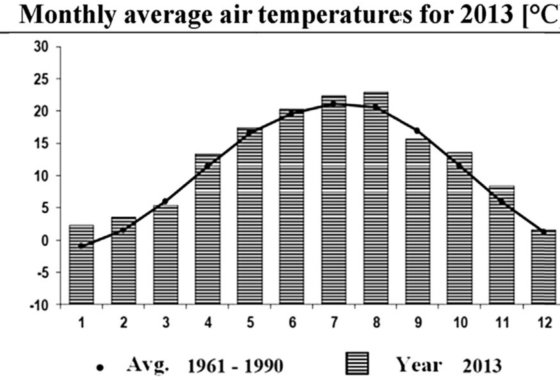



**Fig. 5.** Electricity utilization for 2011, 2012 and 2013.

**Table 3**
Monthly heating energy utilization and outdoor air temperatures for 2013.

| Month | Heating [kWh] | Monthly average air temperatures for 2013 [°C] |
|---|---|---|
| Jan | 115993 | |
| Feb | 63473 | |
| Mar | 42323 | |
| Apr | 1415 | |
| Oct | 9551 | |
| Nov | 45003 | |
| Dec | 61030 | |
| **Annual Sum** | **338788 kWh/a**<br>**99 kWh/m²/a** | |




according to people dependent air ventilation amount and eq. (3) filtration heat demand according to area dependent air ventilation amount:

$$Q_P = 25.2 \cdot n \cdot \rho \cdot c \cdot (t_e - t_i) \tag{2}$$

$$Q_A = 2.52 \cdot A \cdot \rho \cdot c \cdot (t_e - t_i) \tag{3}$$

where:

$Q_P$ - Filtration heat demand according to people dependent air ventilation amount, [kJ/h]
$Q_A$ - Filtration heat demand according to area dependent air ventilation amount, [kJ/h]
$n$ - Design value for office occupancy, [−]
$A$ - Room floor area, [m$^2$]
$\rho$ - Density, [kg/m$^3$]
$c$ - Specific heat, [kJ/(kg*°C)]
$t_e$ - Exterior air temperature, [°C]
$t_i$ - Interior air temperature, [°C]

### 2.4. Computational modeling methodology – phase 3

The computational CAD model construction using BIM technology with integration of gathered construction and material data was performed in phase 3.

During the investigation five programs were applied, which were the following:

- Autodesk Revit (3D model design) [30];
- Ecotect Analysis and Radiance (Solar analysis and advanced daylight simulation) [31,32];
- Sketchup (Multi-zone thermal model construction) [33];
- OpenStudio (integration of multi-zone thermal model properties; construction, materials, occupancy, internal loads and schedules) [34] and finally

- EnergyPlus (dynamic energy simulation) [35].

Autodesk Revit software package was chosen for the highly detailed BIM model design of the reference building. The geometric building data generated in Revit are readable, after conversion, for Ecotect Analysis where solar simulations were performed using Radiance rendering. Considering the dynamic energy performance simulation (heat balance calculation method) for energy performance determination the EnergyPlus engine was selected, since it is acknowledged with high accuracy calculations. The OpenStudio platform is connected with the energy simulation engine and simplifies the detailed data input, lowers error risks and gives a transparent overview of the whole input conglomeration.

Ten separate CAD building models were created in Revit Architecture as separate 3D single floor models according to the previously specified WWR and WG values. The modeling methodology and data conversion with program compatibility is presented in Fig. 6.

The Revit CAD model with RVT extension has to be converted into 3D geometry data with DXF extension in order to be importable into Ecotect Analysis program [15]. The lighting intensity simulation, glazing properties, indoor and outdoor environment, and illumination were set up in Desktop Radiance [15]. The imported DXF file is shown in Fig. 7, where the orientation and wide angle camera views were set up for the output results from Radiance.

### 2.5. Multi-criterion building envelope optimization methodology – phase 4

The multi-criterion building envelope optimization methodology consisted of two major steps, which were the following:

- **Step 1** – Optimal WWR and WG determination using multi-criterion optimization. The daylight simulations were performed in Radiance engine in the function of three criteria:
- Advanced spatial daylight dispersion,
- Average indoor daylight factor,
- Automated artificial lighting sensor system for electricity reduction.
- **Step 2** – Determination of Best Case Energy Performance Scenario in the function of glazing properties and climate data using dynamic energy performance simulation. The influence of glazing parameters on the annual heating and cooling energy demand for temperate climate conditions were determined. The following variable parameters were used in the simulation:
- Overall heat transfer coefficient (U-value),
- Solar heat gain coefficient,
- Visible transmittance.

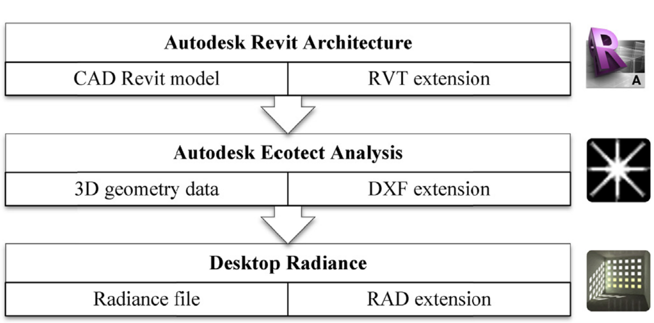



**Fig. 6.** Modeling methodology and data conversion for illumination simulation.

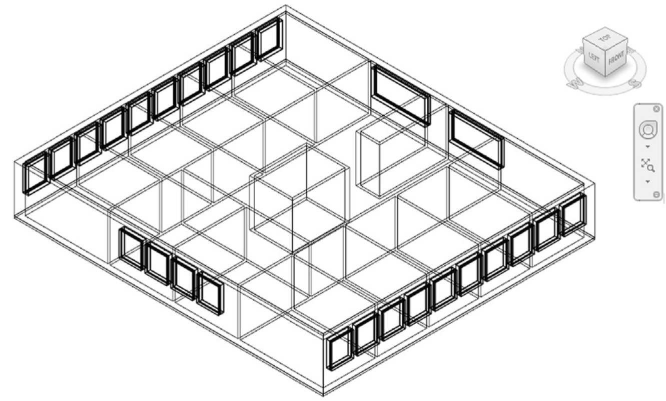


**Fig. 7.** Revit DXF model.

## 3. Building envelope design with multi-criterion optimization – phase 4

### 3.1. WWR, WG and window properties

Daylight intensity was measured in hourly intervals during the winter and summer period with KIMO luxmeter instrument. The monitoring was conducted on the 9th floor's west oriented office, with 50% glazing area. As shown in Fig. 8 the monitored indoor daylight intensities majority during July and August was above visual comfort requirement for office environment.

Indoor illumination dispersion was simulated and analyzed for three WG's shown in Table 4 below. The WG's were selected according to window heights in correspondence with glazing areas. Window heights generated horizontal and vertical rectangular shapes, and square. The WG's from Table 4 were applied for four models with WWR: 20%, 25%, 30% and baseline model's 50%. Windows with minimum 0.5 of visible transmittance index were applied for the daylight dispersion analysis.

#### 3.1.1. Advanced daylight simulation in radiance

The illumination simulation and image rendering was conducted via detailed setup in Radiance Control Panel (CP). The simulation setup was carried out through nine steps, which were divided in five major categories as shown in Fig. 9.

The daylight quality was evaluated according to three criteria: spatial illumination dispersion, average daylight factor during occupied hours, and photo-electric lighting simulation for electricity reduction. The rendering accuracy was setup considering lighting detail, reflections and image quality as shown in Table 5.

A primary simulation was conducted on the baseline model in order to determine average daylight intensity in offices throughout an annual period. The simulation output is a 3D graph which presents average daylight intensities for a single level, as shown in Fig. 10.

As concluded from the results, Fig. 10, average annual daylight intensity was above occupant comfort requirements for East, South and West oriented offices, where the glazing ratio is 50%.

### 3.2. Results

The daylight intensity analysis and daylight dispersion required a complex simulation where the variables were: time, sky conditions and zone orientation. The period setup for simulation was every second month within intervals of 4 h in order to determine the daylight intensity in offices at 8.00 h, 12.00 h and 16.00 h on an annual basis. The illumination intensity and spatial daylight

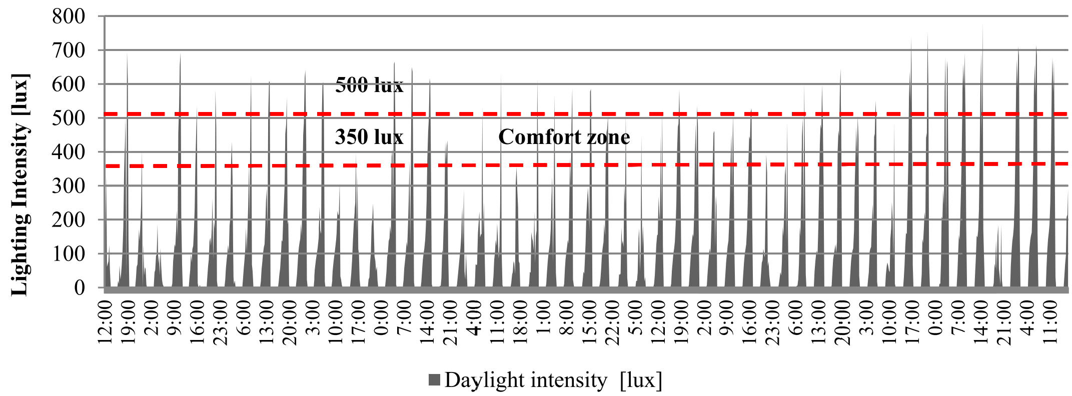
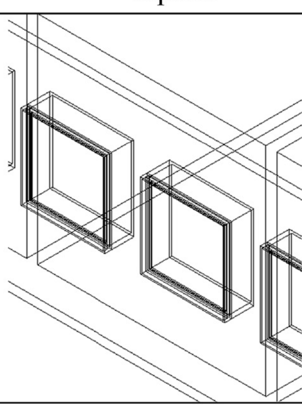
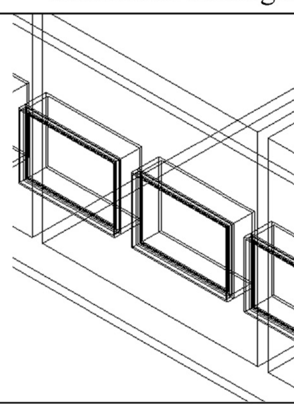
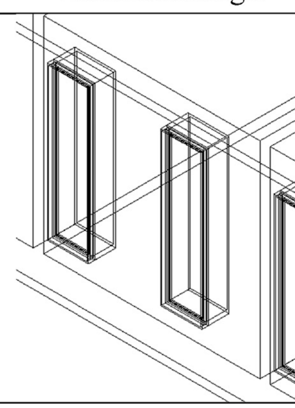



**Fig. 8.** Daylight intensity in West oriented office.

**Table 4**
Window geometries applied for daylight analysis.

| Square | Horizontal rectangle | Vertical rectangle |
|---|---|---|
|  |  |  |

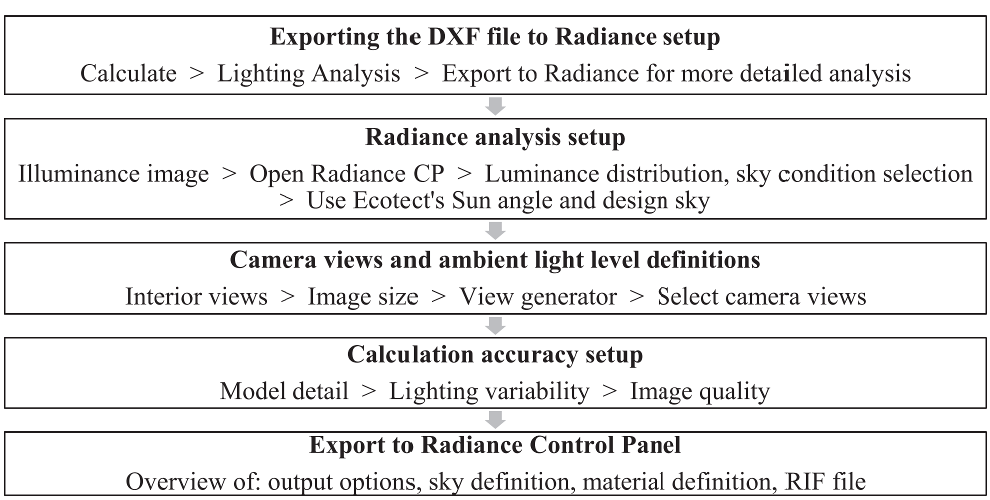



**Fig. 9.** Simulation setup for exporting to Radiance Control Panel.

dispersion was simulated and evaluated within intervals of 350 and 500 lx during occupied hours. 720 simulations were performed in Radiance (3 WWR x 3 W G x 4 orientations x 6 months x 3 intervals = 648 and 72 simulations for the reference model consisting of 4 orientations x 6 months x 3 intervals).

Table 6 presents only selected renders. The indoor daylight dispersion renders were compared and analyzed. Results presented that among the simulated WG's the vertical rectangular window geometry presented the most preferable results due to window height, which contributed to the deepest daylight entrance,

**Table 5**
Rendering properties.

| Render settings | | Illumination scale |
|---|---|---|
| Run identifier | RCP | |
| View type | Interior | |
| Display type | Illuminance [lx] | |
| Max. Reflections | 3 | |
| Lighting detail | Medium | |
| Lighting variability | Medium | |
| Image quality | Medium | |
| Scale | 1000 | |
| Scale division | 10 | |
| Image format | Radiance PIC file | |

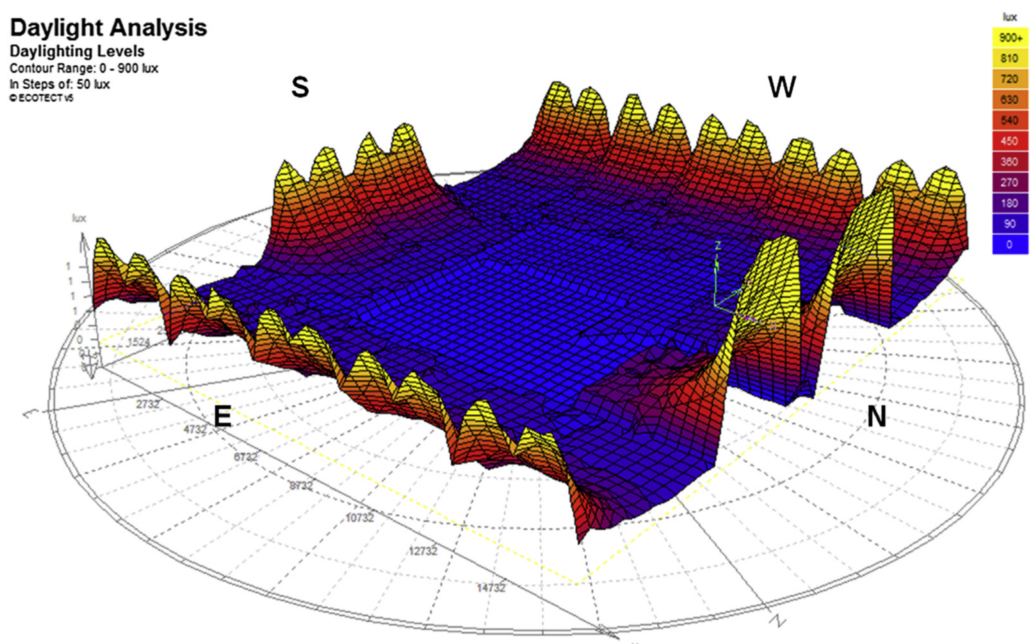




**Fig. 10.** Annual illumination levels.

increasing reflection and dispersion in the indoor environment.

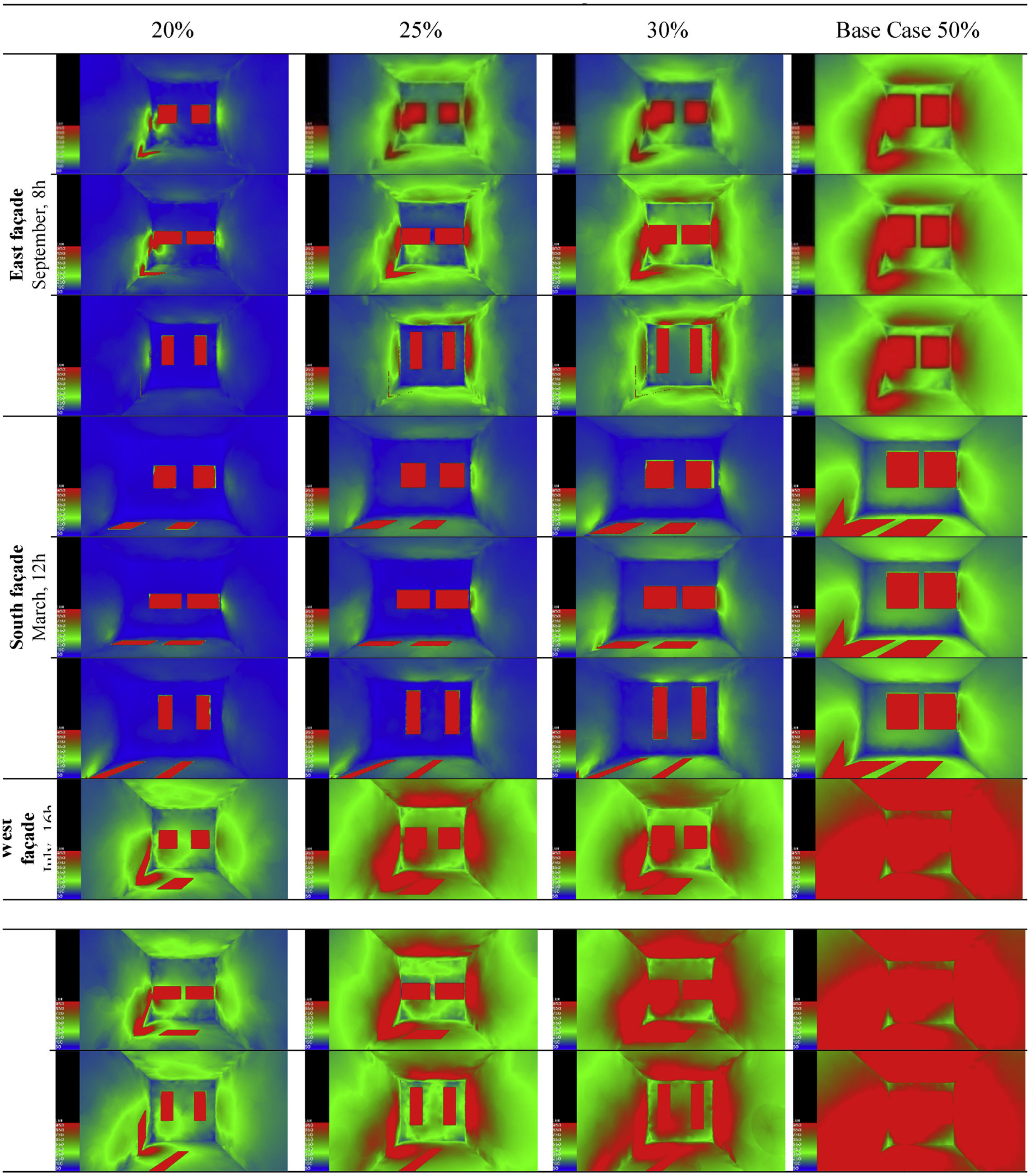
The calculation of average daylight factor (DF) was performed in zone center points utilizing the Building Research Establishment's (BRE) method. BRE is an organization which carries out research and testing for the built environment founded in the United Kingdom. In the research the BRE geometric version of the Split Flux Method was applied in the DF determination for WWR of 20%, 25%, 30%, and base case 50%. The results closest to 2.0 DF were adopted since it satisfied the minimal illumination quality in an office environment. In order to reduce the demand for electric lighting two photoelectric modes were simulated parallel for electric lighting: on/off mode and dimming switch mode [36].

The total number of performed simulations was 16, and the calculated DF's determined the final decision of WWR selection for the optimal building envelope. Two selected calculations are presented in Fig. 11 both with identical properties: East orientation, 30% WWR, vertical rectangular windows, min. daylight intensity for sensor system is 350 lx. The left graph presents the results of the on-off lighting switch mode, and the right graph shows the results for the dimming mode. Another two selected calculations are presented in Fig. 12 both with identical properties as previously for South orientation.

It was concluded that for identical properties the sensor system in dimming mode presents more efficient results compared to the on-off electric lighting mode. The simulations presented the annual percentage of unnecessary usage of electric lighting in the building according to each orientation. Illumination sensors were determined in geometric center points of zones. The on/off mode and the dimming switch mode adjusted the illumination intensity always to fulfill the minimal requirement of 350 lx. The results are presented in Table 7.

The percentage of unnecessary electric lighting during occupied office hours in the case of East oriented offices with 30% WWR was 69% for the dimming mode throughout an annual period and 47% in

**Table 6**
Selected illumination dispersion renders.




the case of on-off switch mode. Electricity reduction for lighting in the case of South oriented offices of 25% WWR was 70% for the dimming mode throughout the year and 49% in the case of on-off switch mode.

## 4. Energy simulation setup

### *4.1. Construction, occupancy and operation schedules*

The building envelope applied in the simulation was selected according to the thermal insulation requirements of the Serbian

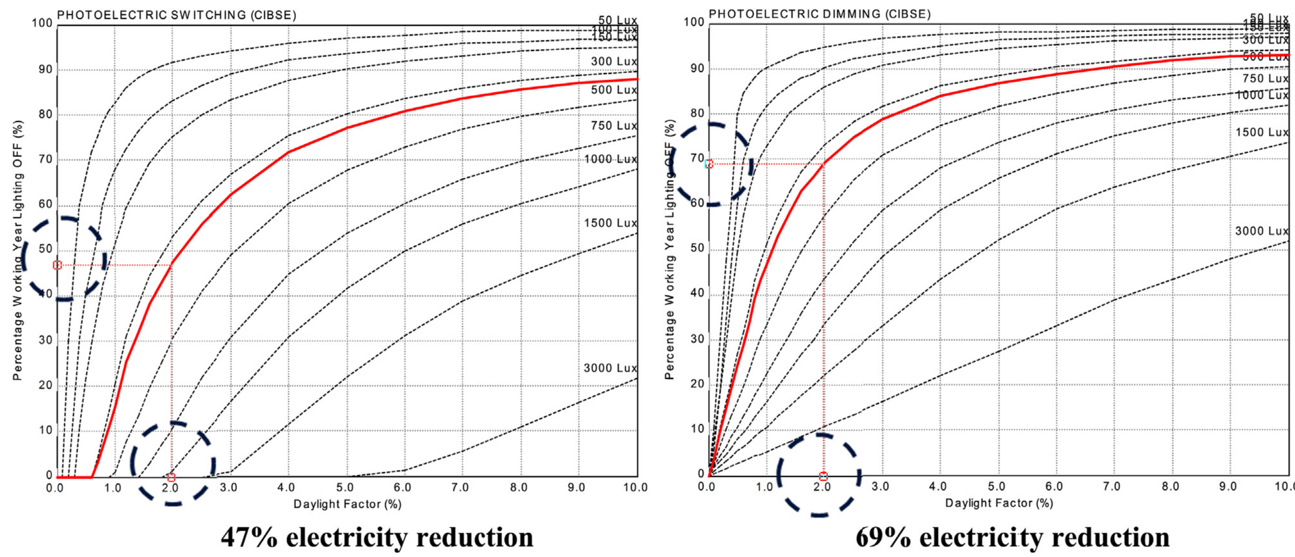



**Fig. 11.** Virtual sensor system for electric lighting: on-off mode (left), dimming switch mode (right) for East orientation, 30% WWR per office.

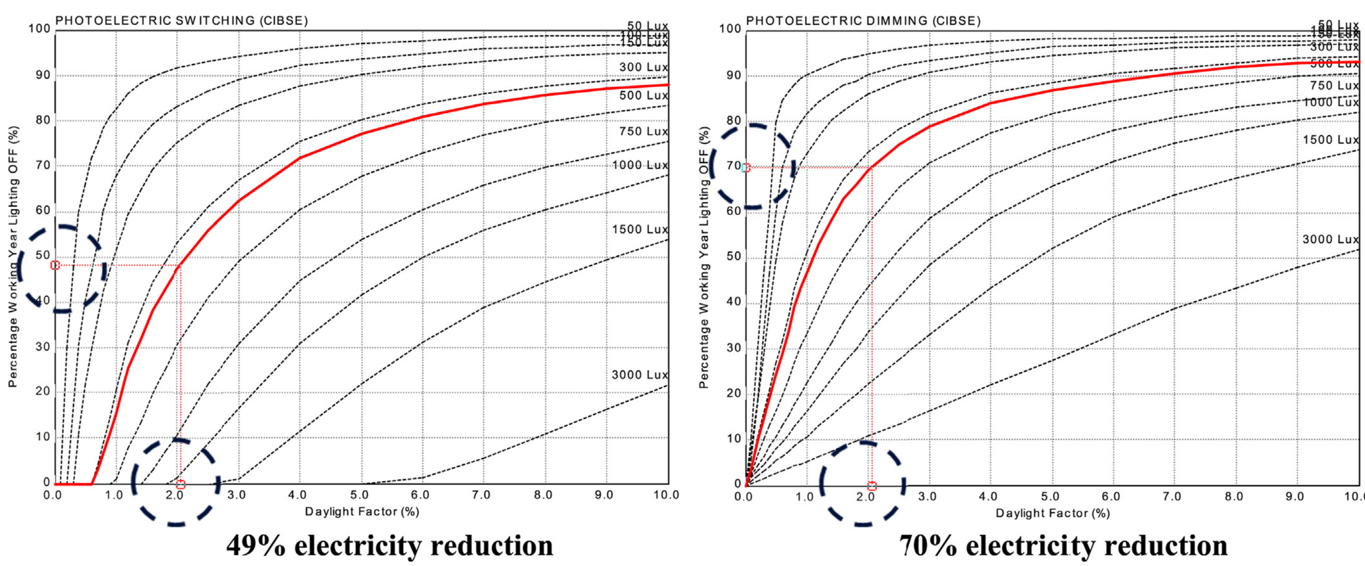



**Fig. 12.** Virtual sensor system for electric lighting: on-off mode (left), dimming switch mode (right) for South orientation, 25% WWR per office.

Directive - Official Gazette RS no. 61/2011 and EU Standard [25,26,29]. The building envelope construction was improved in order to reduce the heat transfer coefficient. The U-value of the existing office building's exterior walls is 2.32 W/(m$^2$K) since the walls are constructed from 25 cm fired clay brick, without insulation layer. The modified exterior wall construction compared to the existing is presented in Table 8 below, where the new U-value is reduced to 0.22 W/(m$^2$K) by adding expanded polystyrene on exterior walls. Furthermore it was recorded that the existing glazing has poor thermal performance, U-value of 2.788 W/(m$^2$K).

The number of occupants was implemented in the energy simulation setup by the following steps:

1. Expectable number of occupants was calculated;
2. Occupied office areas were calculated;
3. Unoccupied areas were calculated.

The expectable number of occupants on building levels is shown in Table 9.

The expected number of occupants on levels from 4 to 9 the space floor area per person equals 10.8 m$^2$/person. On the 3rd level equals 24.5 m$^2$/person and on the 2nd level is 16.33 m$^2$/person. Finally on the ground level if approximated to total office area on a single level, as done previously, the space floor per person is 13.3 m$^2$/person.

### 4.2. Internal energy loads

Internal energy loads (heat gains) from occupants, lighting and equipment were modeled. In offices occupant activity is majorly sedentary where the metabolic rate is equal to 1.2 MET (69.87 W/m$^2$), thus, a normal person will have the heat loss of approximately 120 W.

Thermostat schedules were set up for the heating and cooling period. Temperature limits were defined according to thermal comfort criteria. The minimum temperature limit for the heating

**Table 7**
Daylight factor calculation with photoelectric dimming, adopted WWR [%].

| | | | |
|---|---|---|---|
| **East (min 350lx)** | | | |
| WWR | DF | Percentage working year lighting off (%) | |
| 20% | 1.19 DF | 53 | – |
| 25% | 1.39 DF | 58 | – |
| 30% | 1.97 DF | 69 | WWR 30% E/30′ rotation (Adopted) |
| 50% | 3.49 DF | 81 | – |
| **South (min 350lx)** | | | |
| WWR | DF | Percentage working year lighting off (%) | |
| 20% | 1.73 DF | 65 | – |
| 25% | 2.05 DF | 70 | WWR 25% S/30′ rotation (Adopted) |
| 30% | 2.32 DF | 74 | – |
| 50% | 3.98 DF | 83 | – |
| **West (min 350lx)** | | | |
| WWR | DF | Percentage working year lighting off (%) | |
| 20% | 1.30 DF | 56 | – |
| 25% | 1.51 DF | 60 | – |
| 30% | 1.78 DF | 66 | WWR 30% W/30′ rotation (Adopted) |
| 50% | 3.49 DF | 81 | – |
| **North (min 350lx)** | | | |
| WWR | DF | Percentage working year lighting off (%) | |
| 20% | 1.89 DF | 67 | WWR 20% N/30′ rotation (hall) (Adopted) |
| 25% | 2.11 DF | 71 | WWR 25% N/30′ rotation (office) (Adopted) |
| 30% | 2.21 DF | 72 | – |
| 90% | 16.85 DF | 92 | – |

period was set to 21 °C and for the cooling period the maximum temperature limit was 25 °C in compliance with the requirements of the II comfort category limits from EN 15251 [23].

Electric equipment definition was imported in OpenStudio from the Building component library (BLC) as "ASHRAE_189.1–2009 Climate Zone 1–3 Large Office Whole Building Electric Equipment Definition" [37,38]. The specified electric equipment energy requirements were imported as a default value from the BLC library, 5.812514 W/m$^2$.

Light definitions were imported identically from the BLC library in OpenStudio as "ASHRAE_189.1–2009 Climate Zone 1–3 Large Office Whole Building Lights Definition" [37,38]. The energy demand of electric lights was 9.687519 W/m$^2$.

### 4.3. Applied glazing types and parameters

Ten various glazing types were applied according to the window properties (U-value, Solar Heat Gain Coefficient (SHGC) and Visible Transmittance (VT)) as shown in Table 10. The selection of glazing types was between U-values from 0.7 W/(m$^2$K) and 1.7 W/(m$^2$K), SHGC values from 0.22 to 0.75, and VT from 0.39 to 0.81 [39].

The energy simulation will indicate the heating and cooling demands and assess the influence of window parameters.

## 5. Energy performance results and evaluation

Electric lighting and equipment electricity demand per square meter of floor area required 44 kW h/m$^2$/a annually. Monthly electricity demands are shown in Fig. 13. These internal loads were adopted as constant loads in all scenarios with the internal energy gains produced by their operation. EnergyPlus simulations in cover the following:

- Determination of heating and cooling energy demands in the case of 10 Scenarios and
- Evaluation of glazing influence on the annual energy performance (heating and cooling demand).

The selection of efficient glazing is concentrated on finding a correlation between the heating and cooling demand. Findings indicated the significance of the SHGC's influence on the annual heating and cooling demand. Energy performance results for all Scenarios are presented in Figs. 14 and 15 where monthly peak and deep values are shown in bold for each month.

The highest energy demand for heating was recorded in Scenario W1, 39,243 kW h/a, while Scenario W10 presented the lowest

**Table 8**
Exterior wall construction with material properties.

| Existing exterior wall | | Optional exterior wall | |
|---|---|---|---|
| Exterior wall layers | Material properties | Modified exterior wall layers | Material properties |
| 10 mm Cement mortar | U = 1.73 [W/(m$^2$K)] | 10 mm Cement mortar<br>120 mm Fired clay brick | U = 0.93 [W/(m$^2$K)]<br>d = 0,1016 [m]<br>c = 0,89 [W/(m*K)]<br>ρ = 1920 [kg/m$^3$]<br>Q = 790 [J/(kg*K)] |
| 250 mm Fired Clay Brick | d = 0,1016 [m]<br>c = 0,89 [W/(m*K)]<br>ρ = 1920 [kg/m$^3$]<br>Q = 790 [J/(kg*K)] | 100 mm Insulation | d = 0,1016 [m]<br>c = 0,03 [W/(m*K)]<br>ρ = 24 [kg/m$^3$]<br>Q = 1210 [J/(kg*K)] |
| | | 250 mm Fired clay brick | d = 0,1016 [m]<br>c = 0,89 [W/(m*K)]<br>ρ = 1920 [kg/m$^3$]<br>Q = 790 [J/(kg*K)] |
| 5 mm Cement mortar<br>U = 2.32 [W/(m$^2$K)] | U = 1.73 [W/(m$^2$K)] | 5 mm Cement mortar<br>U = 0.28 [W/(m$^2$K)] | U = 0.93 [W/(m$^2$K)] |

**Table 9**
Occupant number and approximated office areas.

| No. of occupants | Building level | Office area approx. [m$^2$] | |
|---|---|---|---|
| (18 × 6) 108 pers. | 4th – 9th level | (196 × 6) 117 | Office area: 1897 m$^2$ |
| 8 pers. | 3rd level | 19 | Other: 1533 m$^2$ |
| 12 pers. | 2nd level | 19 | (Entrance, hall, corridor, staircase, elevators, WC, sub-station spaces, installation spaces, archive) |
| 16 pers. | 1st level | 19 | |
| 10 pers. | Ground level | 133 | |
| Rarely occupied | Basement | 0 | |
| Total 154(Adopted 160 pers.) | Total no. 11 levels | Total area: 3430 m$^2$ | |

**Table 10**
Applied window types.

| Scenario | Windows | Properties | |
|---|---|---|---|
| W1 | Dual pane | U-value | 1.70 [W/(m$^2$K)] |
| | PilkingtonOptifloat-clear | SHGC | 0.60 [–] |
| | | Visible Trans. | 0.70 [–] |
| W2 | Dual pane | U-value | 1.30 [W/(m$^2$K)] |
| | PilkingtonOptifloat-clear | SHGC | 0.50 [–] |
| | | Visible Trans. | 0.73 [–] |
| W3 | Tri-pane | U-value | 0.90 [W/(m$^2$K)] |
| | PilkingtonPlanar + Optifloat + K Glass | SHGC | 0.34 [–] |
| | | Visible Trans. | 0.57 [–] |
| W4 | Tri-pane | U-value | 0.70 [W/(m$^2$K)] |
| | PilkingtonPlanar + Optifloat + Optitherm | SHGC | 0.23 [–] |
| | | Visible Trans. | 0.42 [–] |
| W5 | Dual pane | U-value | 1.67 [W/(m$^2$K)] |
| | Pilkington, Energy Advantage, | SHGC | 0.75 [–] |
| | Argon, Low-E, #3 Surface | Visible Trans. | 0.77 [–] |
| W6 | Dual pane | U-value | 1.53 [W/(m$^2$K)] |
| | Guardian Clima-Guard 80/70 | SHGC | 0.69 [–] |
| | | Visible Trans. | 0.81 [–] |
| W7 | Tri-pane | U-value | 1.05 [W/(m$^2$K)] |
| | One pane with Sun-Stop coating | SHGC | 0.34 [-] |
| | and Argon | Visible Trans. | 0.63 [-] |
| W8 | Tri-pane | U-value | 0.70 [W/(m$^2$K)] |
| | Two panes with Sun-Stop coating and Argon | SHGC | 0.31 [–] |
| | | Visible Trans. | 0.54 [–] |
| W9 | Tri-pane | U-value | 0.80 [W/(m$^2$K)] |
| | PilkingtonPlanar + Optifloat + K Glass | SHGC | 0.22 [–] |
| | | Visible Trans. | 0.39 [–] |
| W10 | Tri-pane | U-value | 0.70 [W/(m$^2$K)] |
| | PilkingtonPlanar + Optifloat + Optitherm | SHGC | 0.26 [–] |
| | | Visible Trans. | 0.52 [–] |

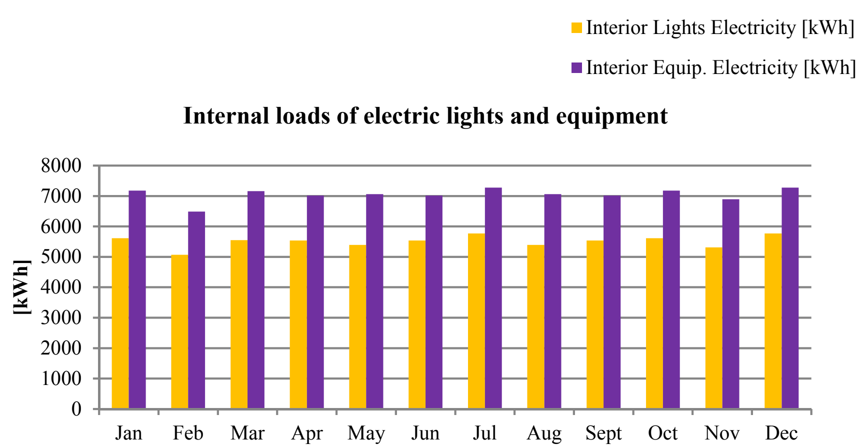



**Fig. 13.** Electric lighting and equipment loads.

heating demand of 27,773 kW h/a, as shown in Fig. 14. When the SHGC values were compared, the lowest 0.22 and 0.26 values of Scenarios W9 and W10 presented lowest energy demands since the energy gains from the solar rays are low (22–26%) which resulted in less energy needs for cooling compared to scenarios with higher SHGC values. The heating demand is lower due to constant internal heat gains specific for office environments which maintains in the building since 22–26% escapes through the glazing.

In order to evaluate the energy demand of the building and the importance of SHGC influence, annual cooling energy demand was analyzed respectively. The simulations for the cooling demand presented higher values compared to the heating demands due to high internal gains. The highest energy demand for cooling, Fig. 15, was recorded in Scenario W5, 17,8597 kW h/a, while Scenario W9 presented the lowest cooling demand, 96,886 kW h/a. The heating energy accumulation in the interior is influenced by the SHGC index. High SHGC values transmit more solar energy into the interior as in Scenario W5 with 75% energy transmission which is manifested in high indoor solar gains, which resulted in approximately 45% higher cooling demands compared to the lowest result from W9 and 41% higher cooling demands compared to W10.

The primary criterion for selection was low overall annual energy demand of building. Followed by the following selection criteria:

- Equal or lower U-value as defined in regulations;
- Low SHGC value (equal or below 0.3);
- VT value (above 0.5).

Scenarios W4, W8, W9 and W10 resulted in less deviation

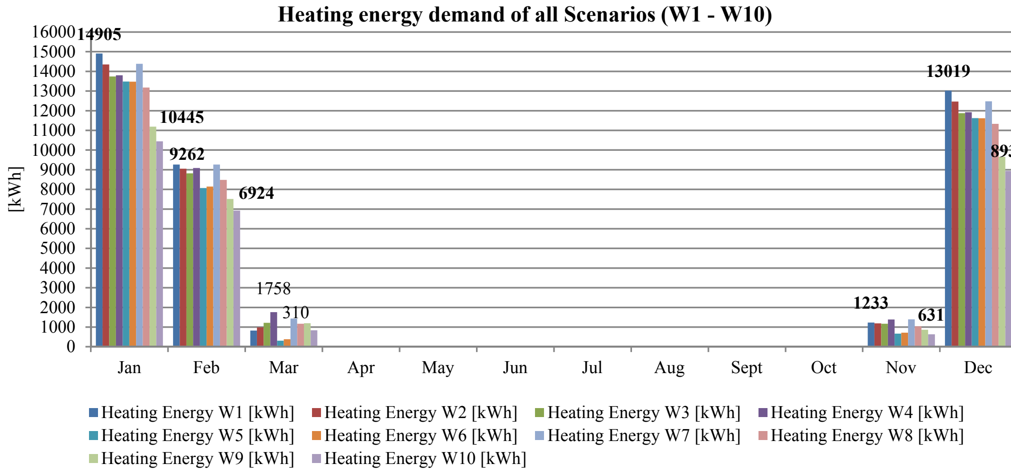



**Fig. 14.** Heating energy demand of all Scenarios.

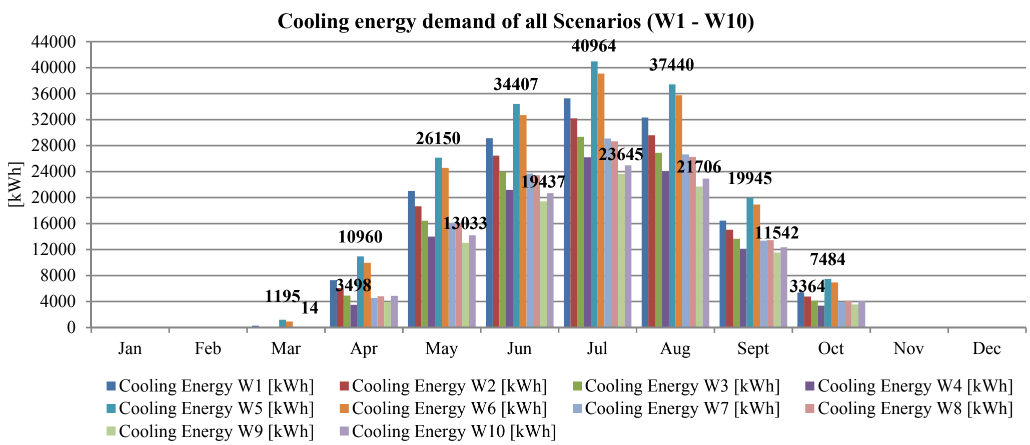



**Fig. 15.** Cooling energy demand of all Scenarios.

between heating and cooling demands compared to scenarios W5 and W6. Scenarios W5 and W6 are inadequate for the temperate climate of Novi Sad since the SHGC coefficients were the highest. These two scenarios are preferable for colder climates. Scenarios W1, W2, W3, W7 and W8 resulted in similar heating demands between 35 MW h and 39 MW h, while the cooling demands varied between 117 MW h and 147 MW h.

Finally the W10 Scenario was adopted due to the highest visible transmittance value 0.52 since in the simulations for the daylight dispersion analysis the applied glazing's VT value was above 0.5. It was concluded that the SHGC coefficient had:

- Major influence considering external solar energy gains and
- Indoor energy maintenance from occupants, electric lights and equipment.

The thermal transmittance did not take a crucial part in the heating and cooling demand influence. As for example Scenario W7 and W8 had U-values of 1.056 W/(m$^2$K) and 0.704 W/(m$^2$K), but the results of the total annual energy demand was similar; 156 MW h in the case of Scenario W7 and 152 MW h for Scenario W8. It can be concluded that the energy demands as previously stated are mostly affected by the SHGC coefficient since similar coefficients will have the results with only slight deviation among each other.

### 5.1. Air-ventilation energy demand determination according to EN 15251

Table 11 presents the annual energy amount for area and people dependent air ventilation according to eq. (2) and eq. (3). It was assumed that the ventilation is in constant function 8 h daily during weekdays throughout an annual period. $Q_A$ stands for the energy demand of area dependent ventilation and $Q_P$ for the energy demand of people dependent ventilation.

Area dependent air ventilation energy ($Q_A$) resulted is 19,138 kW h/a, where the highest energy demands (above 3 MW h/month) were obtained during the winter period; November, December and January, due to significant air temperature difference. Considering the people dependent air ventilation energy ($Q_P$) identical period presented the highest energy demands (above 4 MW h/month) for outdoor air preparation, whereas total annual energy demand resulted in 25,517 kW h. Fig. 16 presents a graphical overview in monthly values of area and people dependent air ventilation energy demand. Both peak values were in January (4.7 MW h and 3.5 MW h), while both lowest energy demands were in August (42 MW h and 32 MW h).

In conclusion the total annual energy demand for both area and people dependent ventilation presented 44655 kW h/a where the energy demand per m$^2$ is 37.2 kW h/m$^2$/a. The total energy demand

**Table 11**
Area and people dependent air ventilation energy.

| Mon. | No. people | A [$m^2$] | $q_b$ [$m^3h^{-1}$] | ρ [$kgm^{-3}$] | c [kJ* $kg^{-1}C^{-1}$] | $t_e$ [°C] | $t_i$ [°C] | Δt [°C] | $Q_A$ [$kJh^{-1}$] | $Q_A$ [$kJs^{-1}$] [kW] | $Q_A$ [kWh] 8 h/d | $Q_P$ [$kJh^{-1}$] | $Q_P$ [$kJs^{-1}$] [kW] | $Q_P$ [kWh] 8 h/d |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Jan | 160 | 1200 | 3024 | 1.27 | 1.005 | 0.4 | 21 | −20.6 | 79,509 | 22.1 | 3534 | 1,06,013 | 29.4 | 4712 |
| Feb | 160 | 1200 | 3024 | 1.26 | 1.005 | 2.3 | 21 | −18.7 | 71,608 | 19.9 | 3183 | 95,477 | 26.5 | 4243 |
| Mar | 160 | 1200 | 3024 | 1.24 | 1.005 | 7.3 | 21 | −13.7 | 51,629 | 14.3 | 2295 | 68,838 | 19.1 | 3059 |
| Apr | 160 | 1200 | 3024 | 1.21 | 1.005 | 12.7 | 21 | −8.3 | 30,522 | 8.5 | 1357 | 40,696 | 11.3 | 1809 |
| May | 160 | 1200 | 3024 | 1.19 | 1.005 | 18.0 | 22 | −4.0 | 14,466 | 4.0 | 643 | 19,288 | 5.4 | 857 |
| Jun | 160 | 1200 | 3024 | 1.18 | 1.005 | 20.8 | 23 | −2.2 | 7890 | 2.2 | 351 | 10,519 | 2.9 | 468 |
| Jul | 160 | 1200 | 3024 | 1.17 | 1.005 | 22.4 | 23 | −0.6 | 2133 | 0.6 | 95 | 2845 | 0.8 | 126 |
| Aug | 160 | 1200 | 3024 | 1.17 | 1.005 | 22.2 | 23 | −0.8 | 2845 | 0.8 | 32 | 3793 | 1.1 | 42 |
| Sep | 160 | 1200 | 3024 | 1.20 | 1.005 | 16.9 | 21 | −4.1 | 14,952 | 4.2 | 665 | 19,937 | 5.5 | 886 |
| Oct | 160 | 1200 | 3024 | 1.21 | 1.005 | 12.6 | 21 | −8.4 | 30,890 | 8.6 | 1373 | 41,186 | 11.4 | 1830 |
| Nov | 160 | 1200 | 3024 | 1.24 | 1.005 | 7.1 | 21 | −13.9 | 52,382 | 14.6 | 2328 | 69,843 | 19.4 | 3104 |
| Dec | 160 | 1200 | 3024 | 1.26 | 1.005 | 1.7 | 21 | −19.3 | 73,905 | 20.5 | 3285 | 98,540 | 27.4 | 4380 |
| **Annual sum** | | | | | | | | | | | **19,138** | **Annual sum** | | **25,517** |

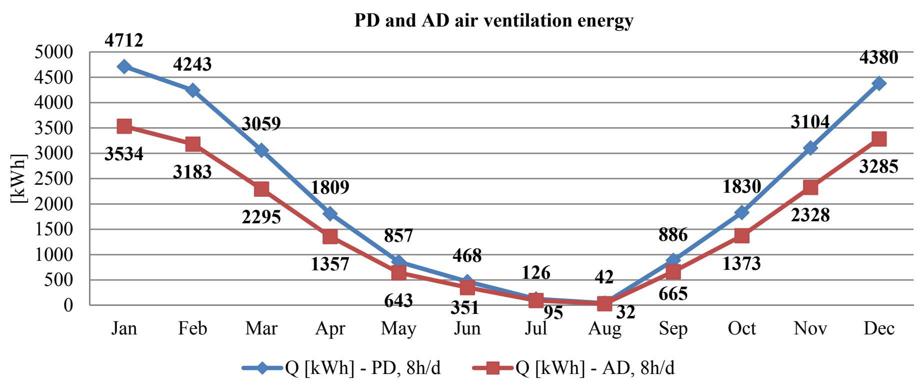



**Fig. 16.** Monthly average people dependent (PD) and area dependent (AD) air ventilation energy.

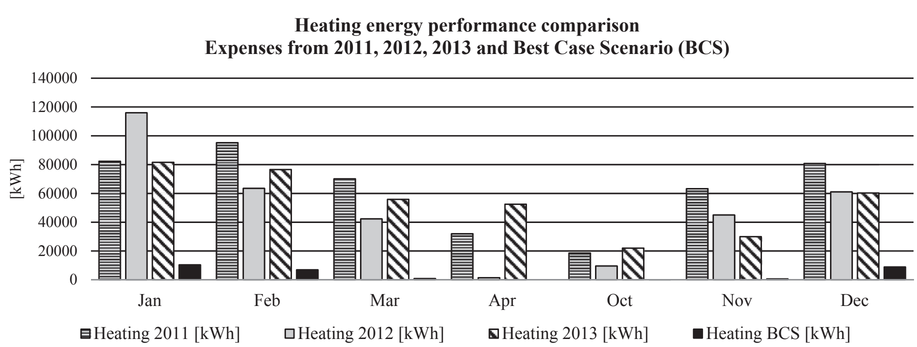



**Fig. 17.** Heating energy performance comparison.

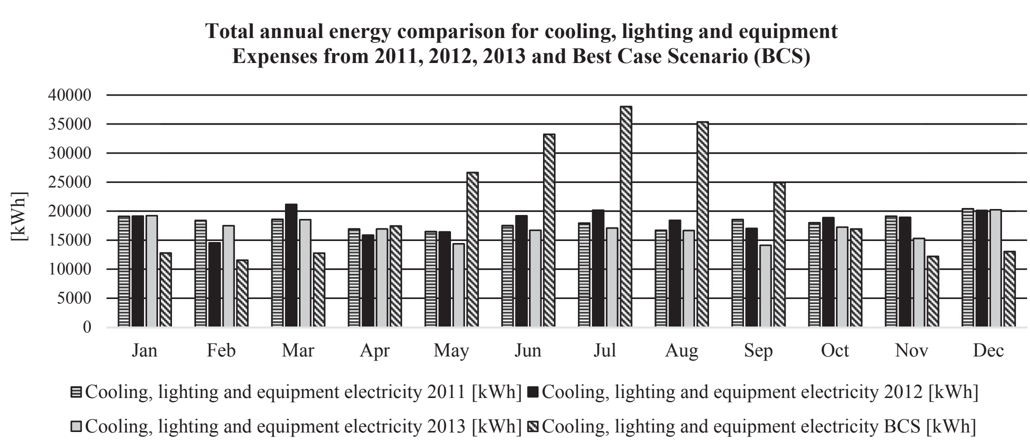



**Fig. 18.** Heating energy performance comparison.

**Table 12**
Energy performance comparison.

| Month | Reference office building (2011) | | Reference office building (2012) | | Reference office building (2013) | | Best case scenario | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Heating energy [kWh] | Cooling, lighting and equipment electricity [kWh] | Heating energy [kWh] | Cooling, lighting and equipment electricity [kWh] | Heating energy [kWh] | Cooling, lighting and equipment electricity [kWh] | Heating energy [kWh] | Cooling energy [kWh] | Energy demand for lighting and equipment (100% usage) [kWh] | |
| Jan | 82306 | 19099 | 115993 | 19158 | 81610 | 19214 | 10445 | 0 | 5617 | 7180 |
| Feb | 95210 | 18376 | 63473 | 14544 | 76527 | 17478 | 6924 | 0 | 5067 | 6490 |
| Mar | 70106 | 18595 | 42323 | 21141 | 55891 | 18519 | 834 | 55 | 5548 | 7159 |
| Apr | 31934 | 16918 | 1415 | 15870 | 52467 | 16918 | 0 | 4881 | 5537 | 7015 |
| May | / | 16486 | 0 | 16411 | / | 14375 | 0 | 14197 | 5392 | 7060 |
| Jun | / | 17519 | 0 | 19203 | / | 16706 | 0 | 20685 | 5537 | 7015 |
| Jul | / | 17947 | 0 | 20164 | / | 17078 | 0 | 24960 | 5773 | 7278 |
| Aug | / | 16707 | 0 | 18402 | / | 16652 | 0 | 22917 | 5392 | 7060 |
| Sep | / | 18541 | 0 | 17014 | / | 14113 | 0 | 12369 | 5537 | 7015 |
| Oct | 18580 | 18009 | 9551 | 18883 | 21980 | 17245 | 1 | 4127 | 5617 | 7180 |
| Nov | 63268 | 19124 | 45003 | 18922 | 30005 | 15282 | 631 | 0 | 5313 | 6896 |
| Dec | 80788 | 20398 | 61030 | 20111 | 60304 | 20230 | 8939 | 0 | 5773 | 7278 |
| Sum [kWh/a] | 442192 | 217719 | 338788 | 219823 | 378784 | 203810 | 27773 (+37325 EN15251) | 104191 (+7330 EN15251) | 21153 | 84626 |
| [kWh/m²/a] | 129 | 64 | 99 | 64 | 110 | 59 | 19 | 32 | 31 | |

for heating and cooling according to the adopted Scenario W10 was 131964 kW h/a where the energy demand per m$^2$ of floor area equals 38.47 kW h/m$^2$/a. Finally, the total heating and cooling energy demand with the added air preparation energy demand for the Best Case Scenario resulted in total 1,76,619 kW h/a, where the energy demand per m$^2$ of floor area equals 51.49 kW h/m$^2$/a.

## 6. Comparison of energy performance simulation results with annual expenses

Comparison of annual energy demands between reference office tower building and the Best Case Scenario are presented in Figs. 17 and 18 and Table 8 as numerical values. Fig. 17 presents the comparison of monthly heating expenses and heating demands from the simulated Best Case Scenario. The findings presented that if the U-value of exterior walls is reduced to 0.7 W/m$^2$K and for exterior glazing stands below 1.0 W/m$^2$K with SHCG value below 0.3, than the annual heating energy demand for the office building in temperate climate conditions reaches a significant reduction up to 85%.

In Fig. 18 highest demands were obtained for cooling in the period from May to September in the case of the Best Case Scenario, since occupant thermal comfort requirements where implemented in the thermostat schedules for winter and summer period according to EN 15251.

In Table 12 annual energy expenses of the reference multi-level office building from 2011, 2012 and 2013 are compared with the adopted Best Case Scenario. The annual heating energy utilization in the case of reference building per m$^2$ of single floor area was 129 kW h/m$^2$/a in 2011, 99 kW h/m$^2$/a in 2012, and 110 kW h/m$^2$/a in 2013 with unsatisfied indoor environmental standards.

The heating energy demand according to the Best Case Scenario is 85% less compared to 2011 expenses, 80% less compared to 2012 and 83% compared to 2013. The Best Case Scenario has satisfactory indoor environmental standards since the thermostat schedules were set up according to the winter and summer thermal comfort requirements.

The calculation of annual heating and cooling demand for the Best Case Scenario was performed according to the EN 15251 Annex B; Basis for the criteria for indoor air quality and ventilation rates; B.1 Recommended design ventilation rates in non-residential buildings [36], as seen in Table 8 Best Case Scenario results column. According to the climatic conditions of Novi Sad and EN 15251; 37 MW h/a, were added to the simulated heating energy and 7 MW h/a for the cooling energy, since an ideal air load system was simulated in EnergyPlus without the modeling of air preparation process.

The heating energy demands of the Scenarios were various, highly influenced by the characteristics of the windows. It was concluded that the SHGC coefficient had:

The thermal transmittance did not take a crucial part in the heating and cooling demand influence. As for example Scenario W7 and W8 had U-values of 1.056 W/(m$^2$K) and 0.704 W/(m$^2$K), but the results of the total annual energy demand was similar; 156 MW h in the case of Scenario W7 and 152 MW h for Scenario W8. The SHGC values were the following; 0.33 for Scenario W7 and 0.31 for Scenario W8. It can be concluded that the energy demands as previously stated are mostly affected by the SHGC coefficient since similar coefficients will have the results with only slight deviation among each other.

## 7. Conclusion

The investigation presented the applicability of the formulated integral methodology which could be both flexible and adaptable for application in various climatic conditions and for different building energy efficiency directives and regulations. The developed multi-objective methodology consisting of four major phases was demonstrated on a reference office building. The integral methodology is formulated to be general, adaptable and applicable which could be widely applied in energy performance refurbishment of existing buildings and help architects and engineers in the early-design stages of new projects.

The investigation presented the significance of building envelope's thermal properties and application of adequate windows on the reduction of annual energy demand in the function of climate conditions. With adequate glazing type the heating energy demand could be reduced by 83% compared to the reference office tower building. The investigation pointed out that the total heating and cooling energy demand including air preparation could be reduced to 51.49 kW h/m$^2$/a, compared to the reference buildings annual energy demand which equaled more than 150 kW h/m$^2$/a.

The results present various possibilities of application, as the following:

- Improving the energy performance of administrative buildings with the same or similar characteristics;
- Rational and efficient use of energy in the building sector;
- Flexibility of the model from the aspect of office building envelope design;
- Providing guidance in the early stages of designing new office buildings;
- Providing guidance in rehabilitation of existing office buildings;
- The optimization method is flexible and can be applied for different climate conditions.

Thermal comfort parameters are included in further directions of investigation in the function of minimizing annual heating and cooling loads, yet maintaining a comfortable indoor environment. In order to find a reasonable solution for cooling energy demand reduction, further research will include the simulation of night time ventilation to determine the cool air accumulation capacity of the building.

The formulated optimization methodology in this paper is presented on a reference office building of the Faculty of Technical Sciences located in temperate climate region, since all necessary technical data were available and energy monitoring system was installed. Future investigations will cover the testing of the integral methodology's performance for buildings located in cold and warm climate regions.

Economical aspect is highly important when improving the thermal properties of building envelope. Materials and construction expenses will be taken into consideration according to the performance and investment aspect of an ongoing project.

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