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Influence of WWR, WG and glazing properties on the annual heating and cooling energy demand in buildings

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Abstract

This investigation presents a detailed analysis in an effort of building energy performance improvement from the aspect of building envelope influence on the annual heating and cooling demand. The aim is to indicate methods of performative intervention for envelope improvement and to offer architects and practitioners useful information for decission-making in the rehabilitation and improvement process of existing office buildings. Building envelope was investigated in order to determine preferable window to wall ratio's (WWR) and window geometry (WG) in the function of indoor daylight quality in offices via numerical simulations in Radiance engine, followed by the assessment of glazing influence on the annual energy demand. A comparative analysis was performed among gathered annual building expenses and simulated heating and cooling demands from the multi-zone thermal model constructed in EnergyPlus engine. Findings from the dynamic simulations indicated the influence of glazing parameters on the annual heating and cooling demand of the multi-zone building model.

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Keywords: Building envelope; illumination quality; energy performance; Radiance; EnergyPlus

1. Introduction

The investigation elaborates building envelope performance both from glazing perfromance and thermal performace aspects. Illuminaton performace analysis has been a widespread topic investigated in numerous papers

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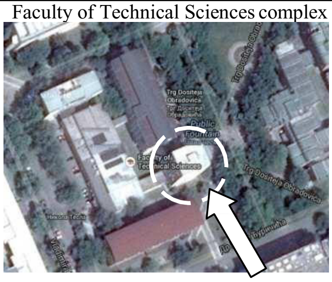
via simplified models, daylight coefficient concept, daylighting schemes, window properties, building design and climate conditions [1, 2, 3, 4, 5, 6, 7]. Thermal and lighting simulations from the energy perspective were investigated in previous researches applying energy modeling [8]. Envelope glazing's transmittance dependence on the solar radiation in order to reduce building energy demand was investigated respectively from wavelength and economic aspects respectively [9, 10]. An optimized model for envelope improvement and energy performance rehabilitation in temperate climatic conditions of Vojvodina Province in Serbia has still not been elaborated from the aspect of illumination performance analysis. The research was conducted on a typical not rehabilitated 10 level reference office building which is part of the Faculty of Technical Sciences complex in Novi Sad. The adopted best case indoor illumination performance scenario was simulated in EnergyPlus with the aim to explore and determine the annual heating and cooling energy demand. The possibility of application can be realized in building envelope rehabilitation and improvement of existing office buildings with similar characteristics.

2. Materials and methodology

The selected 10 level reference "FTS office tower" building (3430 m^2) which is part of the Faculty of Technical Sciences complex in Novi Sad, Serbia was monitored in the sub-station during a period for three months in Winter of 2014 in order to assess its heating energy demand. Energy expenses for district heating and electricity were gathered for the year 2012 in order to compare them with the results from the simulation. The building used in total 378 MWh/a (110 kWh/m^2/a) for district heating on an annual basis, and 203 MWh/a (59 kWh/m^2/a) for electricity; combined cooling, lighting and equipment. The location and climate data of Novi Sad were imported from the global climatological database Meteonorm 7 [11] as shown in Tab. 1.

Table 1. Reference office building location and 3D model

Properties:	Novi Sad map from Meteonorm 7	3D FTS office tower 10 levels	Faculty of Technical Sciences complex
City: Novi Sad Country: Serbia Province: Vojvodina Climatic zone = III, 3 Latitude = 45.333° Longitude = 19.850° Altitude = 84 m Building orientation is rotated 30° anti-clockwise from North axes.	 Faculty of Technical Sciences complex		 FTS office tower

In order to determine annual heating and cooling loads a multi-zone thermal model was constructed using OpenStudio plug-in for Sketchup. Each thermal zone was assigned with internal load properties typical for a large office building. The thermal zones were formed and named according to their function and position in the building. According to the investigation phases and complexity of the model and simulation processes, five programs were applied for this study, which are the following: Autodesk Revit Architecture (3D model design) [12], Autodesk Ecotect Analysis and Desktop Radiance (Solar analysis and advanced daylight simulation) [13, 14], Sketchup (Multi-zone thermal model construction) [15], OpenStudio (integration of multi-zone thermal model properties; construction, materials, occupancy, internal loads and schedules) [16] and finally EnergyPlus (dynamic energy simulation) [17].

3. Modeling of building envelope in the function of daylight intensity

3.1. Window to wall ratio and window geometry

The research involves the determination of preferable window to wall ratio (WWR) and window geometry (WG) in the function of illumination dispersion analysis, average daylight factor and electric lighting reduction. Indoor illumination dispersion is simulated and analyzed for three geometries shown in Tab. 2 below. The WG's from Tab. 2 were applied for four models with WWR's: 20 %, 25 %, 30 % and baseline model's 50 %.

3.1.1. Advanced daylight simulation in Radiance

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 daylight simulation setup and image rendering was conducted via detailed setup in Radiance which was divided in five major categories as seen in Fig. 1. Primary 3D geometric models with different WWR's and WG's were created in Revit program and converted into files with DXF extensions, importable into Radiance via Ecotect Analysis program. The second category refers to the environment and sky condition setup in Radiance, followed by the illumination scale definition (0-1000lx), camera positioning and image generator. Finally the rendering accuracy was setup considering lighting detail, reflections and image quality as seen in Tab. 3. Before starting the simulation and image rendering the setup properties were overviewed once again in the Radiance Control Panel.

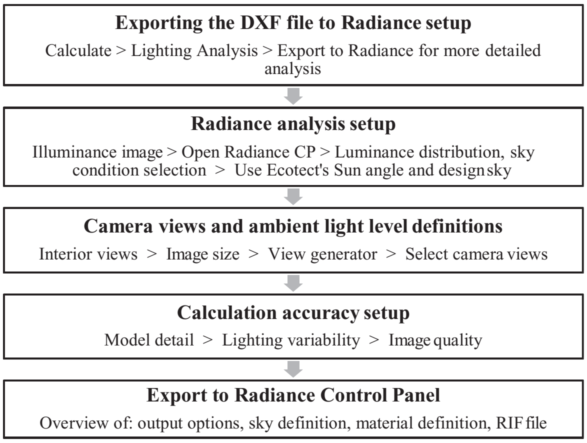


Fig. 1. Simulation setup for exporting to Radinace Control Panel

Table 2. Window geometries applied for daylight analysis

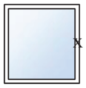
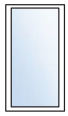
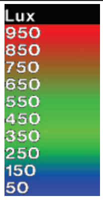
Square	Horizontal rectangle	Vertical rectangle
a x a 	x b 	x b 

Table 3. Rendering properties

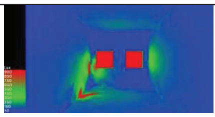
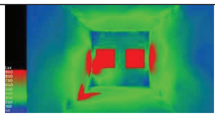
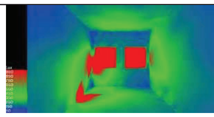
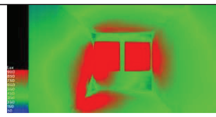
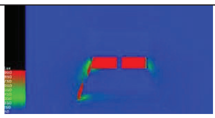
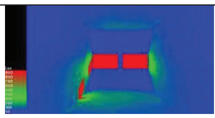
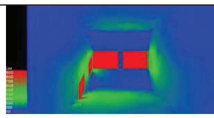
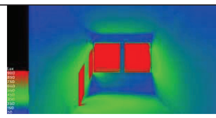
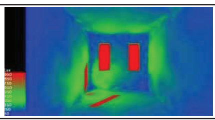
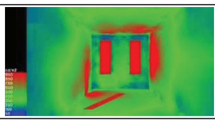
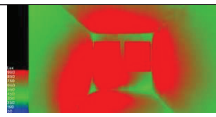
Illumination scale	Render settings	
	Run identifier:	RCP
	Display type:	Illuminance [lx]
	Max. Reflections:	3
	Lighting detail:	Medium
	Lighting variability:	Medium
	Image quality:	Medium
	Scale:	1000
	Scale division	10

The daylight intensity analysis and daylight dispersion required numerous simulations which depended on the analyzed period, time, sky conditions and zone orientation. The period setup for the simulation was the 15th of every second month within intervals of 4h in order to determine the daylight intensity in offices at 8.00h, 12.00h and 16.00h on an annual basis. The illumination intensity and spatial daylight dispersion was simulated and evaluated within intervals of 350 and 500 lx during occupied hours. The lighting quality was demonstrated through daylight dispersion analysis which consisted of simulating 3 WWR's for 3 WG's and 4 orientations for the prior stated intervals. The reference model was included in the simulation respectively. 720 simulations were performed in Radiance (3 WWR x 3 WG 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). All output images were evaluated according to the illumination intensity between 350 and 500 lx. In Tab. 4 only selected renders are presented. From the comparative analysis the vertical rectangular window geometry presented the most preferable results due to window height which contributed to deeper daylight dispersion in the indoor environment resulting in qualitative natural illumination in offices. Window frames were disregarded in the simulations.

The calculation of average daylight factor (DF) was performed in zone centre points as BRE DF calculation for WWR of 20%, 25%, 30%, and base case 50%. Results closest to 2.0 DF were adopted since it satisfies the minimal illumination quality in an office environment. DF simulations were applied for previously selected vertical rectangular window geometry and the total number of conducted calculations was 16 (4 orientations x 4 WWR's).

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. The simulations presented the annual percentage of unnecessary usage of electric lighting in the building according to each orientation and WWR. 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.

Table 4. Selected illumination dispersion renders

	20%	25%	30%	Base Case 50%
East Sept 8h				
East Mar 8h				
East July 8h				

3.2. Results

Illumination intensity detectors were setup as stated previously and adjusted that if lighting level in the center zone point falls below 350 lx the sensors automatically turn on electric lights or switch to dimming mode. Findings indicated best performance if dimming mode is applied. In conclusion, considering the average daylight factor (DF) and annual percentage of unnecessary usage of electric lighting the adopted scenarios of WWR for vertical WG are presented in Tab. 5.

Table 5. Daylight factor [-], adopted WWR [%] and photoelectric dimming

East Offices	Percentage working year lighting OFF (%)		**West** Offices	Percentage working year lighting OFF (%)	
DF 1.97	69	WWR **30%** / 30˚ rotated floor plan	DF 1.78	66	WWR **30%** / 30˚ rotated floor plan
South Offices	Percentage working year lighting OFF (%)		**North** Corridor	Percentage working year lighting OFF (%)	
DF 2.05	70	WWR **25%** / 30˚ rotated floor plan	DF 1.89	67	WWR **25%** / 30˚ rotated floor plan

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 Directive - Official Gazette RS no. 61/2011 and EU Standard [18, 19, 20]. The overall heat transfer coefficient of existing exterior walls have 2.32 W/(m^{2}K) and existing exterior glazing has 2.78 W/(m^{2}K). The U-value of the modified exterior wall is significantly reduced to 0.22 W/(m^{2}K) by adding 14cm of expanded polystyrene. Further, internal gains from occupants were assigned in OpenStudio in the "people definition" dialog. The number of occupants and internal gains were 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 Tab. 6.

Table 6. Occupant number and approximated office areas

No. of occupants	Building level	Office area approx. [m^2]	
(18 x 6) 108 pers.	4th – 9th level	(196 x 6) 1176	Office area: 1897 m^2 Other: 1533 m^2 (Entrance, hall, corridor, staircase, elevators, WC, sub-station spaces, installation spaces, archive)
8 pers.	3rd level	196	
12 pers.	2nd level	196	
16 pers.	1st level	196	
10 pers.	Ground level	133	
Rarely occupied	Basement	0	
Total 154 (adopted 160 pers.)	Total no. 11 levels		Total area: 3430 m^2

Occupancy is defined according to the occupancy intensity in the function of occupied period, and people activity in the function of the occupied period. The "Run Period Profiles" were formulated as a Priority 1 profile for weekdays (8 hours) followed by Priority 2 for Saturday (4 hours) and Priority 3 (0 hours) for Sunday. Electric lighting, electric equipment and thermostat schedules for heating and cooling were also assigned according to the occupancy intensity and building operation hours.

4.2. Applied glazing types and parameters

Glazing types were applied according to window properties (parameters: U-value, Solar Heat Gain Coefficient, Visible Transmittance) as shown in Tab. 7. The selection of glazing types was among U-values of 1.3 W/(m^{2}K) and 0.7 W/(m^{2}K) high performance tri-pane Pilkington glasses with low-E mainly applied for cold climate conditions [21]. The low-E coating directs infrared heat created inside the building, either from absorbed sunshine or generated from a furnace or other heating source, back inside. The energy simulation will indicate the heating and cooling demands and assess the influence of window parameters.

Table 7. Window properties

Scenario	Windows	Parameters		
W1	Dual pane; Pilkington, Optifloat clear	U-value 1.30 W/(m^{2}K);	SHGC 0.50;	VT 0.73
W2	Tri-pane; Pilkington, One pane with Sun-Stop coating and Ag	U-value 1.056 W/(m^{2}K);	SHGC 0.338;	VT 0.63
W3	Tri-pane; Pilkington, Planar + Optifloat + Optitherm glass	U-value 0.70 W/(m^{2}K);	SHGC 0.26;	VT 0.52

5. Results and evaluation – heating and cooling demands

Prior to heating and cooling demand determination the building envelope glazing was improved according to the following criteria: 1. Indoor illumination dispersion analysis, 2. Daylight factor calculation, and 3. Photo-electric lighting simulation for electricity reduction. As stated previously from the daylight dispersion simulation, vertical windows contributed to the deepest daylight declination in offices, and according to the average DF the adopted WWR for East and West orientated offices was 30%, for South offices 25% and for the corridor on the North 20%. Finally, photoelectric lighting simulation was applied in order to reduce the annual electricity requirement by an average of 70% in case of dimming mode simulation.

The annual heating and cooling energy demands of the three Scenarios are compared in Fig. 2 and 3. Scenario W1 presented the highest annual energy demands in total 50 kWh/m^2/a. Scenario W2 had a slightly lower total demand of 46 kWh/m^2/a. W3 Scenario had a total annual demand of 38 kWh/m^2/a. The annual energy demand reduction of Scenario W3 was 17% lower compared to Scenario W2 and 24% lower compared to W1.

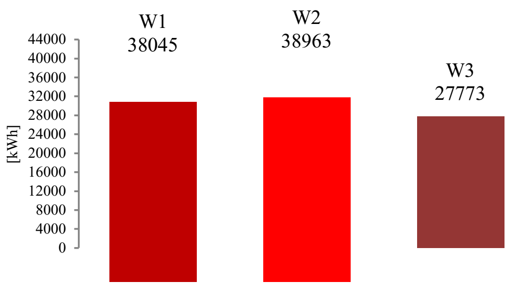


Fig. 2. Annual heating energy demand (W1-W3)

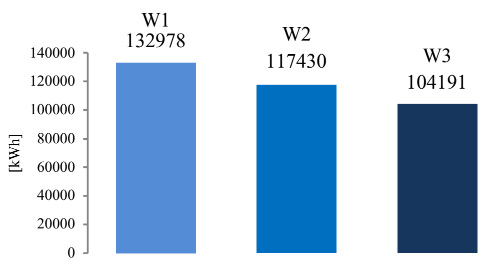


Fig. 3. Annual cooling energy demand (W1-W3)

Finally the W3 Scenario was adopted as the most preferable among the simulated and was compared with the reference FTS tower's energy performance as presented in Tab. 8, below. The total energy demand of the Best Case Scenario (W3) could be reduced roughly by 83% in case of annual heating. Simulated cooling energy demand was 40% higher compared to annual heating due to internal heat gains of occupants and electric equipment, specific for office environments.

Table 8. Energy performance comparison

Reference FTS office tower energy expenses (2012)			Best Case Scenario energy demand – W3		
	Heating energy [kWh]	Cooling, lighting and equipment electricity [kWh]	Heating energy [kWh]	Cooling energy [kWh]	Energy demand for lighting and equipment [kWh]
Sum	378784	203810	27773	104191	106330
			EN 15251; air ventilation amount + 37325 (for heating) + 7330 (for cooling)		
[kWh/m^2/a]	110	59	19	32	31

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 [20], as seen in Tab. 8. According to the climatic conditions of Novi Sad and EN 15251; 37 MWh/a were added to the simulated heating energy and 7 MWh/a for the cooling energy, because an ideal air load system was simulated in EnergyPlus with neglection of the air preparation procedure.

6. Conclusion

The investigation presented the significance on the reduction of annual energy performance of building envelope's thermal properties and the application of adequate windows in the function of climate conditions and building type. WWR and WG can be analyzed from the aspect of daylight dispersion and daylight factor in order to offer performable results for improvement of indoor environmental quality in offices. The WWR per single office was decreased from 50% to 30% and 25% per single office exterior wall area depending on the orientation, and by application of adequate glazing type the heating energy demand could be reduced by 83% compared to the reference office tower building. Thermal comfort parameters are included in the 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.

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