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Research paper

ENERGY PERFORMANCE ANALYSIS OF A BUILDING USING OPENSTUDIO AND ENERGYPLUS

Tijana Živković[1]

Abstract

This paper analyses the energy performance of an architectural building, the Visitor Centre within the Ćele Kula (Skull Tower) memorial complex in Niš, using the OpenStudio and EnergyPlus software tools. The aim was to assess the influence of architectural decisions, materials, the building envelope, orientation and climatic conditions on the overall energy efficiency of the building. The paper describes the architectural and functional organisation of the building, the modelling of its geometry, the formation of thermal zones and the definition of space-use schedules required for an accurate simulation. Simulations were carried out for three levels of envelope thermal insulation, two building orientations and three climatic locations (Niš, Copenhagen and Athens). Particular attention was paid to the selection of materials and glazing systems, including solar-radiation control by means of brise-soleil and the definition of transparent elements with appropriate U-factor and SHGC values, which directly affect heat gains and losses. The results show that improved insulation and better glazing do not by themselves guarantee lower energy use; their effect depends on the climatic context and on the control of solar gains, so that a measure beneficial in a cold climate may increase the cooling demand in a warm one.

Key words: *energy efficiency, building energy simulation, building envelope, climate, EnergyPlus*

[1] Student, Faculty of Civil Engineering and Architecture, University of Niš, Niš, Serbia; tijana2002zivkovic@gmail.com; ORCid 0009-0008-3641-0577

1. INTRODUCTION

Buildings account for a substantial share of global energy use, between 20% and 40% in developed countries, which makes their energy efficiency a key priority for both policy and design [1, 2]. The subject of this paper is the analysis of the energy performance of an architectural building using the OpenStudio and EnergyPlus software tools. The building selected for the analysis is the Visitor Centre within the Ćele Kula memorial complex in Niš (basement and ground floor, B+GF). It is free-standing and compact in form, with façade openings on all four sides for daylighting and natural ventilation, an insulated envelope, a flat roof with linear roof lanterns, and movable timber panels (brise-soleil) for solar-radiation control. The moderation of heating and cooling loads through climate-responsive envelope, orientation and solar-control decisions is a long-established principle of bioclimatic design [3, 4]. Such design decisions make it a suitable example for examining the influence of architectural design on energy efficiency.

The analysis was carried out through variant solutions covering three levels of envelope thermal insulation (V1, V2 and V3), two orientations (0° and 180°) and three climatic locations, Niš, Copenhagen and Athens. The building was modelled in OpenStudio (geometry, seventeen thermal zones, systematic naming of elements, surface matching and IDF export) and simulated in EnergyPlus on the basis of climate (EPW) files, operating schedules, internal loads, HVAC control and the thermal properties of the materials and glazing. Standard heat-balance algorithms were applied (TARP and DOE-2 for convection, the CTF method for conduction). Building performance simulation of this kind is a well-established approach for assessing energy demand and comparing design alternatives before construction [5]. The aim is to assess the influence of design decisions, orientation, envelope and climate on the building's overall energy demand.

2. ARCHITECTURAL AND FUNCTIONAL CONCEPT OF THE BUILDING

The Visitor Centre is located near the Ćele Kula monument, separated to the east by the Gabrovačka River, with a bridge providing a direct pedestrian link (Figure 1).

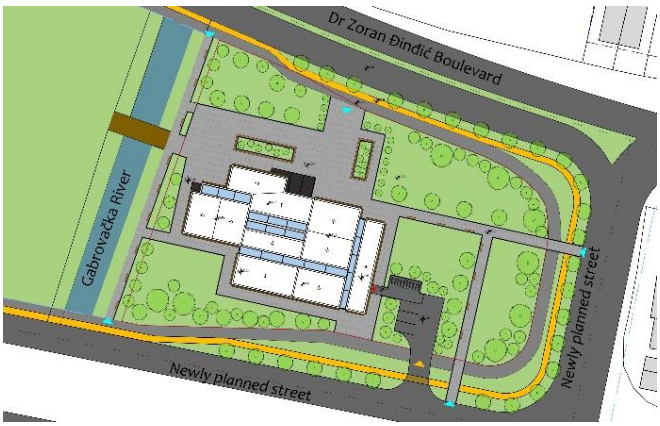


Figure 1. Site plan of the designed building, Author (AutoCAD)

Technical rooms occupy the basement; the ground floor contains the entrance (porter's lodge, ticket office, reception and cloakroom), a central hall, a bookshop with a souvenir area, the exhibition spaces (the permanent display and the memorial room dedicated to Stevan Sinđelić), a multipurpose hall to the south and the administration in the western wing, providing a clear visitor route from the entrance to the exit towards the monument (Figure 2).

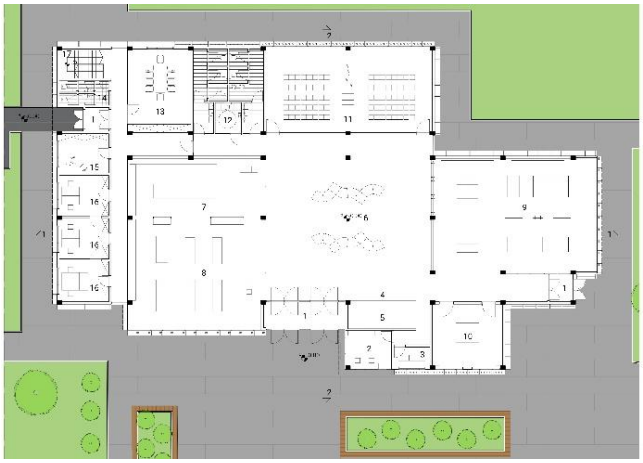


Figure 2. Floor plans of the designed building, Author (AutoCAD)

Façade openings on all four sides enable uniform daylighting and natural ventilation, the eastern façade establishing a visual link with the monument, while their dimensions are balanced against heat losses and gains (Figure 3). The envelope is compact, with insulated external walls, a flat roof with linear roof lanterns and a ground-bearing floor, and movable timber brise-soleil that reduce summer overheating and allow passive solar gains in winter. On this basis the energy model was created and simulated through the variant solutions described below.



Figure 3. Section and Elevations of the Designed Building, Author (AutoCAD)

3. OPENSTUDIO MODELLING METHODOLOGY

The analysis was carried out in OpenStudio, an open-source platform built on the EnergyPlus engine, used as a SketchUp plug-in that links the architectural 3D model

directly to EnergyPlus [6]. The geometry followed the design documentation (dimensions, storey heights, openings and the boundaries of the heated space); the building comprises seventeen spaces and, besides windows and a curtain wall, fixed roof windows (light strips). The model was checked through the render by surface type and render by boundary condition views (Figure 4 and Figure 5).

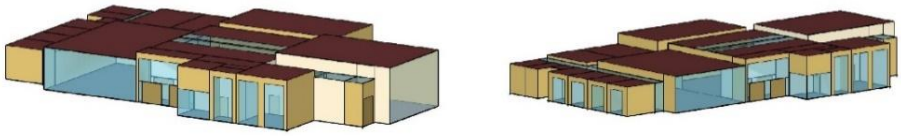


Figure 4. Model in the render by surface type view, Author (OpenStudio)

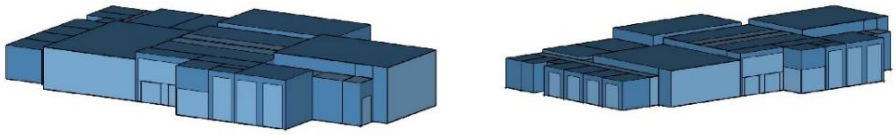


Figure 5. Model in the render by boundary condition view, Author (OpenStudio)

All elements were named systematically (surfaces by function and orientation, spaces and zones by purpose), and the Surface Matching procedure with the Intersect option ensured the correct connection of adjacent surfaces and accurate inter-zone heat exchange. The building was divided into seventeen thermal zones, with public, administrative and technical rooms treated as separate units, after which the model was exported to the IDF format for simulation in EnergyPlus.

4. ENERGYPLUS SIMULATION METHODOLOGY

In EnergyPlus, a widely used and validated whole-building energy simulation program [7], the building's energy behaviour was simulated from climate data, envelope characteristics, internal gains and modes of use. General settings were mostly left at their defaults (EnergyPlus 25.1; zone sizing; an annual run; City environment; Full Exterior solar distribution; Timestep 6), with the Building class North Axis set to 0° or 180° for the orientation variants. Standard algorithms were applied – TARP and DOE-2 for convection, the CTF method for conduction and the Third Order Backward Difference scheme for the zone air heat balance, following established heat-balance methods [8]. The manually defined classes that shaped the simulation variants are summarised below.

4.1. Location, climate and simulation period

The Site:Location class was set for three cities depending on the variant – Niš (43.32° N, 21.90° E, +1, 198 m), Copenhagen (55.68°, 12.57°, +1, 14 m) and Athens (37.98°, 23.73°, +2, 42 m) – each with its own EPW climate file and design days (SizingPeriod:DesignDay). The annual simulation (RunPeriod) ran from 1 January to 31 December, with daylight saving from the last Sunday in March to the last Sunday in October (Figure 6).

Field	Units	Obj1	Obj2	Obj3
Name		Nis	Kopenhagen	Atina
Latitude	deg	43.3192	55.6759	37.9839
Longitude	deg	21.8959	12.5655	23.7278
Time Zone	hr	1	1	2
Elevation	m	198	14	42
Keep Site Location Information		No	No	No

Figure 6. Site:Location class, Author (EnergyPlus)

4.2. Schedules and their limits

Using ScheduleTypeLimits, the permitted ranges of schedule values were defined (Fraction, On/Off, Control Type, Temperature, Activity Level, Any Number), and with Schedule:Compact time-varying modes of use were created per room type (offices, vestibules, staircases, sanitary facilities, meeting and conference rooms, the memorial room, corridors and other public spaces), together with schedules for infiltration, equipment, the heating and cooling setpoints and HVAC control. These were linked to the People, Lights and ElectricEquipment classes, to infiltration and to thermostatic control.

4.3. Materials, glazing systems and constructions

Within the Material class, the non-transparent materials of the walls, floors and roof were defined to match the actual design layers, reproducing their thermal storage, conductivity and capacity [9] (Figure 7).

Field	Units	Obj1	Obj2	Obj3	Obj4	Obj5
Name		Krecni malter Zid	Opekarski blok 25	Kamena vuna SZ	Vazdusni sloj	WPC Drvena imitac
Roughness		MediumRough	Rough	VeryRough	Smooth	MediumSmooth
Thickness	m	0,015	0,25	0,12	0,04	0,018
Conductivity	W/m-K	0,72	0,6	0,035	1	0,15
Density	kg/m3	1800	800	80	1,2	600
Specific Heat	J/kg-K	1000	1000	1030	1000	1800
Thermal Absorptance		0,9	0,9	0,9	0,9	0,9
Solar Absorptance		0,7	0,7	0,7	0,7	0,7
Visible Absorptance		0,7	0,7	0,7	0,7	0,7

Figure 7. A part of the Material class, Author (EnergyPlus)

Three window types were defined with WindowMaterial:SimpleGlazingSystem in accordance with the national Rulebook on the Energy Efficiency of Buildings [10] and the broader European energy-performance framework [2], each with a U-factor and an SHGC; these three glazing levels, together with the level of envelope insulation, form the basis of variants V1, V2 and V3 (Figure 8).

Field	Units	Obj1	Obj2	Obj3
Name		Jednostruko staklo I	2struko niskoemisivn	3struko niskoemisivn
U-Factor	W/m2-K	5,8	1,5	0,5
Solar Heat Gain Coefficient		0,83	0,61	0,48
Visible Transmittance				

Figure 8. WindowMaterial:SimpleGlazingSystem class, Author (EnergyPlus)

The WindowMaterial:Blind class defined the fixed external timber brise-soleil on the façade openings (slat width and spacing, tilt angle, reflectance and transmittance), while the roof openings remained unshaded (Figure 9); external shading of this kind is a widely studied and effective strategy for controlling solar gains [11]. Layered assemblies were formed in the Construction class and assigned to the surfaces and sub-surfaces.

Field	Units	Obj1
Name		Brisoleji vertikalni
Slat Orientation		Vertical
Slat Width	m	0,2
Slat Separation	m	0,2
Slat Thickness	m	0,00025
Slat Angle	deg	45
Slat Conductivity	W/m-K	221
Slat Beam Solar Transmittance		
Front Side Slat Beam Solar Reflectance		0,3
Back Side Slat Beam Solar Reflectance		0,3
Slat Diffuse Solar Transmittance		
Front Side Slat Diffuse Solar Reflectance		0,3
Back Side Slat Diffuse Solar Reflectance		0,3
Slat Beam Visible Transmittance		0

Figure 9. A part of the WindowMaterial:Blind class, Author (EnergyPlus)

4.4. Geometry, zones and surfaces

The geometry rules (GlobalGeometryRules) and the zone list (Zone) were imported directly from the OpenStudio model. Three zone lists (ZoneList) were formed, vestibules; corridors, staircases and toilets; and other rooms, for the common schedules and infiltration. Non-transparent surfaces used BuildingSurface:Detailed (each with its construction and zone) and transparent ones FenestrationSurface:Detailed (with solar gains and shading interaction), while the internal, mostly glazed partitions were modelled with InternalMass to capture their thermal inertia without additional zoning.

4.5. Internal loads: people, lighting and electric equipment

Occupancy was defined with the People class (the actual number of people per zone, a radiant fraction of 0.7 and an activity schedule); artificial lighting with the Lights class (15 W/m² in offices and 5 W/m² in vestibules, corridors, staircases and toilets); and electric equipment with the ElectricEquipment class for all rooms except the vestibules (the watts/area method).

4.6. Infiltration and HVAC operation

Infiltration was defined with ZoneInfiltration:DesignFlowRate by zone lists (0.5 air changes per hour, constant in time). Through ZoneControl:Thermostat each zone was linked to a thermostat, with control schedules selecting heating or cooling; the control objects were ThermostatSetpoint:SingleHeating and ThermostatSetpoint:SingleCooling, with setpoints of 22 °C for heating and 26 °C for cooling, uniform for all zones (Figure 10). A simplified HVACTemplate:Zone:IdealLoadsAirSystem determined the energy needed to maintain these setpoints, keeping the focus on the building's architectural and thermal characteristics; the sizing factors were set to 1 and the equipment lists and connections were generated automatically.

Field	Units	Obj1
Name		SNGH
Setpoint Temperature Schedule Name		HVACTemplate-Always 22

Field	Units	Obj1
Name		SNGC
Setpoint Temperature Schedule Name		HVACTemplate-Always 26

Figure 10. Thermostat setpoints for heating and cooling, Author (EnergyPlus)

4.7. Simulation outputs

Outputs were defined with Output: VariableDictionary, OutputTable: SummaryReports (all summary) and OutputControl: Table: Style (HTML, joules converted to kWh). The Zone Ideal Loads Total Heating and Total Cooling variables (Output:Variable) and the total heating and cooling energy (Output: Meter) over the simulation period form the basis for comparing the variants.

5. SYNTHESIS OF THE OBTAINED RESULTS

The energy performance was analysed across three climatic contexts (Niš, Copenhagen and Athens), two orientations (0° and 180°), different levels of envelope thermal protection and three window types, with most façade openings protected by vertical brise-soleil and the roof openings unshaded. This makes it possible to examine the interplay of climate, orientation and envelope quality in the demand for heating and cooling.

Each variation label combines the key parameters: the first letter denotes the city (N – Niš, K – Copenhagen, A – Athens), the first number the orientation (0 for 0°, 1 for 180°) and the third element the variant (1 – basic envelope, 2 – improved insulation and windows, 3 – the most energy-efficient variant) (Figure 11).

Variant solutions – insulation of external elements			
Construction type:	V1 **1**	V2 **2**	V3 **3**
External walls – thermal insulation thickness (cm)	0	10	15
Roof – thermal insulation thickness (cm)	0	15	30
Windows – U-value (W/m²K)	5.8	1.5	0.5
Building orientation			
0 0° and 180° (north and south) **1**			
Location			
Copenhagen **K**	Niš **N**	Athens **A**	

Figure 11. Method of labelling the variations, Author

In Niš at the 0° orientation (Figure 12, left), the basic variant shows a very high heating demand, approximately equal to the cooling demand, indicating significant winter transmission losses. With medium insulation and better windows the heating demand drops sharply while cooling rises and becomes dominant, and with the highest insulation and triple glazing heating is minimal while cooling remains high – the building shifts from a heating-dominated to a cooling-dominated regime, additionally intensified by the unshaded skylights. At the 180° orientation (Figure 12, right) the pattern is the same; orientation only slightly shifts the absolute values, while the level of insulation remains the decisive factor. This shift towards cooling as the envelope improves reflects the climate-dependence of energy performance highlighted by Valladares-Rendón et al. [13], indicating that in a temperate climate such as that of Niš the control of solar gains becomes as important as the reduction of transmission losses.

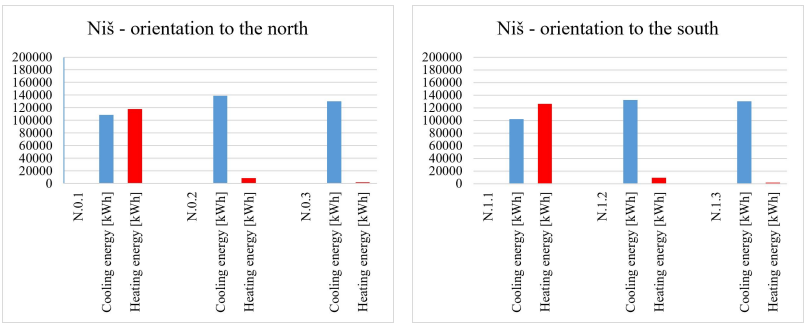


Figure 12. Analysis of the variations for Niš at the 0° (left) and 180° (right) orientation, Author

In Copenhagen (Figure 13) heating strongly dominates the basic variant, several times exceeding cooling, owing to the cold climate and the long heating season. Improving the insulation and windows markedly reduces heating while cooling rises but stays below the levels of warmer climates, and even in the most efficient variant heating remains an important component, which justifies strong insulation in cold climates. The change of orientation produces only minor differences, and improving the envelope clearly reduces the total energy demand, because the reduction in heating outweighs the rise in cooling. This unambiguous benefit of a well-insulated envelope in a heating-dominated climate is consistent with established bioclimatic principles, according to which minimising transmission losses is the primary strategy in cold regions [3, 4].

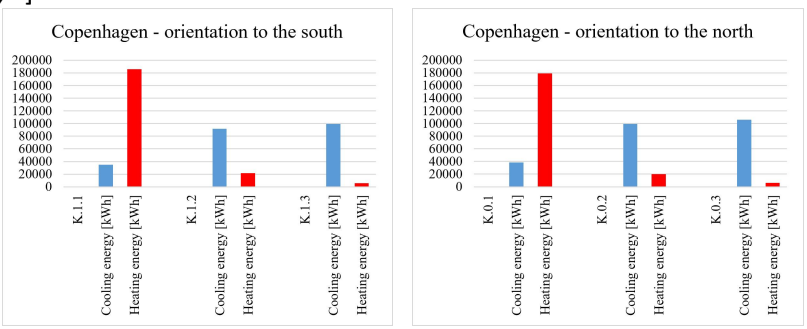


Figure 13. Analysis of the variations for Copenhagen at the 0° (left) and 180° (right) orientation, Author

In Athens (Figure 14) cooling dominates from the basic variant, several times exceeding heating. Increasing the insulation almost eliminates heating, but cooling remains very high and even rises slightly in the middle variant, decreasing only marginally in the most advanced one. Orientation has a more pronounced effect than in the other climates – at 180° the basic variant has noticeably lower cooling than at 0° – but increasing the insulation again raises cooling, confirming that in a warm climate insulation without protection against overheating can increase the cooling load. This agrees with studies of warm-climate design, which stress that controlling solar gains through external shading is more effective than envelope insulation alone for limiting cooling demand [11, 12], while the pronounced effect of orientation observed here supports the emphasis of Valladares-Rendón et al. [13] on combining a favourable orientation with façade shading.

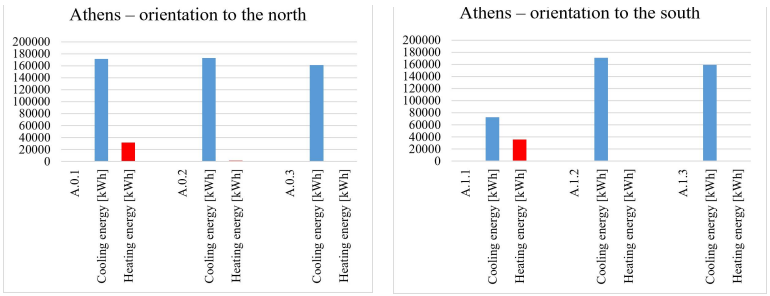


Figure 14. Analysis of the variations for Athens at the 0° (left) and 180° (right) orientation, Author

Comparing the basic variants for all three cities at both orientations clearly shows the influence of the climatic context: Copenhagen is heating-dominated, Niš is approximately balanced with a tendency towards cooling as insulation improves, and Athens is cooling-dominated in all cases. With improved envelopes the differences between the climatic zones grow: in a cold climate better insulation reduces total energy use, whereas in temperate and warm climates it increases the cooling demand, particularly with unshaded skylights. A comparable climate-dependence has been reported at the regional level for Serbian buildings, where horizontal shading elements significantly influenced the energy balance [14], confirming that envelope measures should be matched to climate and combined with solar control rather than applied uniformly.

Overall, the energy performance of a building does not depend solely on thicker insulation and better windows, but on harmonising these measures with the climate and with the control of solar gains. In cold climates a strongly insulated envelope effectively reduces total energy use, whereas in warm climates, without protection against overheating, it can have the opposite effect. Energy-efficient design therefore requires an integrated approach encompassing climate, orientation, envelope characteristics and passive solar-control measures.

6. CONCLUDING DISCUSSION

The analysis of the Visitor Centre within the Ćele Kula memorial complex shows that the architectural design, the arrangement of functional spaces, the envelope characteristics and the solar-control systems have a direct and measurable influence on the building's energy efficiency. Modelling in OpenStudio enabled a faithful reproduction of the geometry, openings, thermal zones and constructions, while simulation in EnergyPlus – with the appropriate climate data, temperature schedules and construction parameters – allowed the energy demand and heat gains to be assessed quantitatively across scenarios.

The simulations confirmed that the level of envelope insulation strongly affects heating and cooling, while orientation influences solar gains and losses, and the comparison of three climatic locations highlighted the building's adaptability and the importance of integrating climatic parameters into design. The carefully defined schedules, internal loads, infiltration and HVAC operation, together with the brise-soleil and roof openings, enabled a realistic full-year assessment of passive solar gains and overheating control. The study confirms that OpenStudio and EnergyPlus are a reliable

methodology for evaluating energy performance and supporting design decisions, capturing the interaction between architectural decisions, climatic factors and the building's modes of use.

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