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EFFECTS OF THE GEOMETRY OF RESIDENTIAL BUILDINGS WITH A SUNSPACE ON THEIR ENERGY PERFORMANCE

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Abstract. *The increase in energy consumption in building design and construction and the issues related to environmental protection have steered many current researchers toward examining the ways to reduce total CO_2 emissions, which resulted in the development of various measures to increase energy efficiency. One measure for more cost-efficient and rational use of energy resources in individual residential buildings is the application of passive solar systems with a sunspace. This paper presents the effects of the shape factor of a residential building with a passive sunspace on the total consumption of heating and cooling energy. The total amount of energy required for building heating and cooling was calculated by means of dynamic modelling using EnergyPlus software. The simulations were run according to the meteorological parameters for the city of Niš. For simulation purposes, models of residential buildings with a passive sunspace and square- and rectangle-shaped floors were designed. The variations between the models include different building shape factor, floor geometry, surface area of the southern façade, and glazing percentage, i.e. window-to-wall ratio (WWR). Examination of the models with WWR=20%, WWR=40%, and WWR=60% revealed that the elongated shape of a building with the aspect ratio of 2.25:1, with the longer side of the façade facing south, is the most favourable in terms of heating energy consumption. For the same WWRs, the elongated shape of a building with the aspect ratio of 1.56:1, with the longer side of the façade facing south, is the most favourable in terms of cooling energy consumption. As WWR increases, so does the amount of energy required to cool the building. The biggest increase in heating energy consumption was observed in buildings with the aspect ratio 1:2.25, with the shorter side facing south.*

Key words: *passive system design, sunspace, residential building, energy efficiency*

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1. Introduction

Since 1990 the emissions of pollutants from fossil fuel combustion in building design and construction have increased by 45% [1]. Through its strategies and action plans, the EU is promoting energy efficiency measures for residential buildings, considering that three quarters of energy demand in building design and construction originate from this very sector. EU directives and strategies have set an ambitious goal to reduce the 1990 CO_2 emissions by 90% by 2050 [2].

Use of passive solar systems can provide up to 50% [3] savings in building heating through the application of specific architectural and urban planning solutions. The geometric characteristics of a building are determined in the early design stages, since the building geometry affects its energy efficiency. Košir et al. analyzed the causality of consumption of the energy required for heating and cooling buildings in Ljubljana depending on their geometry on the one hand and on their window-to-wall ratio (WWR) on the other hand [4]. Their results suggest that, in a humid continental climate and with a low building WWR, energy is prevalently consumed for heating rather than cooling. Heating energy consumption decreases as the WWR increases, which in turn increases the cooling energy consumption. Premrov et al. studied the climate conditions in Athens and Seville for the purpose of determining the energy required for heating and cooling buildings with a wooden construction, characterized by low thermal mass in relation to the WWR, glazing type, and different building geometry [5]. Although numerous authors attempted to establish a correlation between the building shape factor and energy consumption, Granadeiro et al. demonstrated that, with the presence of significant solar gain, the shape factor cannot be an indicator of heating and cooling energy consumption [6].

The results obtained in the present study indicate the total energy required for heating and cooling of a residential building with a passive sunspace depending on the building shape factor, floor geometry, southern façade surface area, and the WWR. The energy performance of a residential building with a passive sunspace system was analyzed for rectangular and square floors. For the set conditions, the EnergyPlus software [7] was used for dynamic modelling in order to determine the amount of energy required for heating and cooling to ensure proper functioning of a building in terms of thermal comfort for the climate area of the city of Niš.

2. Passive Systems with a Sunspace

Passive solar building design allows the maximum penetration of sunlight through the transparent surfaces during the day and its storage within the building structure or thermal mass. Passive systems that collect solar radiation should be designed in accordance with the urban planning parameters and climate conditions of the location (meteorological parameters, terrain, distance from neighbouring buildings, green areas at the location, etc.), for the buildings to be heated as much as possible during the winter and not overheated during the summer. According to the manner of heat transfer, passive systems are classified as direct (solar radiation is received through the windows) or indirect (solar radiation is received by means of a Trombe wall, sunspace, solar air collectors, and the like). [8]

Passive systems with a sunspace consist of glazed portions integrated with the building and used as passive receptors of solar radiation, with the ability to temporarily store it (partition wall, sunspace floor) and transfer it to the building interior. They also represent ‘buffer zones’, as they protect the adjacent interior heated space against sudden external temperature changes.

Figure 1 shows the types of sunspaces according to their placement in relation to the main building (M1–M6), according to the type of partition separating the sunspace from the adjacent room (T1–T4), and according to the position of the thermal mass (A1–A4).

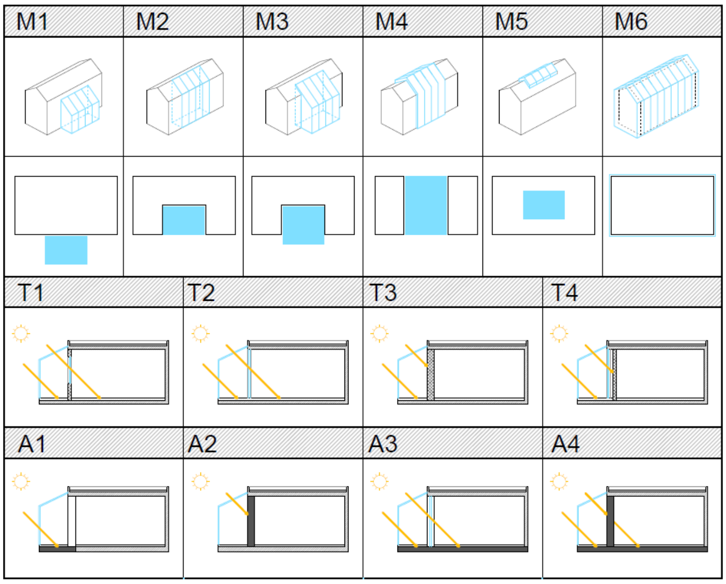


Fig. 1 Types of sunspaces according to: their placement in relation to the main building (M1–M6); the type of partition separating the sunspace from the adjacent room (T1–T4); the position of the thermal mass (A1–A4) [9]

The types of sunspaces according to their placement in relation to the main building (Figure 1) include the following: M1 – attached sunspace; M2 – fully integrated sunspace; M3 – partially integrated sunspace; M4 – laterally integrated sunspace; M5 – atrium sunspace; M6 – sunspace envelope around the primary building. The types of sunspaces according to the type of partition (Figure 1) include: T1 – sunspace with a thermal storage wall and a direct system (window) built into the thermal storage wall; T2 – sunspace with a transparent partition; T3 – sunspace with a thick thermal storage wall; T4 – sunspace with a Trombe wall. The types of sunspaces according to thermal mass position in a single residential building with passive sunspace (Figure 1) include: A1 – thermal mass is the sunspace floor; A2 – thermal mass is the partition wall; A3 – thermal mass is the sunspace and living area floors; A4 – thermal mass is the sunspace and living area floors, as well as the partition wall.

3. METHODOLOGY

3.1. Description of the software

Investigation of energy performance of a residential building with a passive sunspace system for different building shape factor, floor geometry, surface area of the southern façade, and glazing percentage, i.e. window-to-wall ratio (WWR) was conducted using EnergyPlus software.

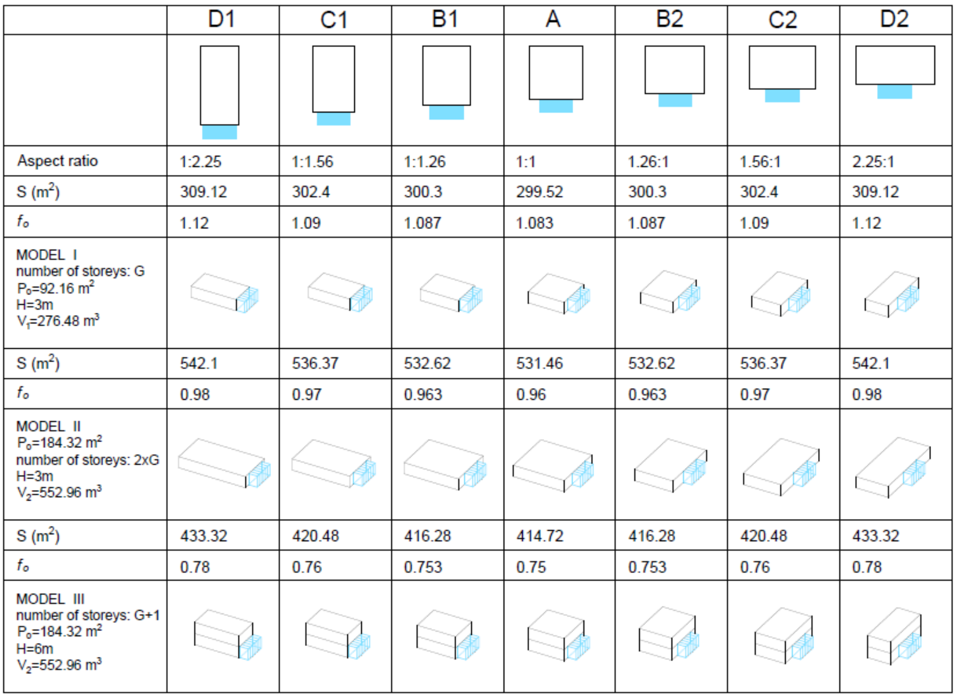
EnergyPlus software is comprised of multiple programme modules forming a whole, which can calculate the energy required for heating and cooling of buildings with different systems or different energy sources [10]. The simulation centres on a model building exposed to various external influences and to different utilization regimes. EnergyPlus software relies on the location and position of the building itself, as well as on meteorological parameters and the external conditions surrounding the building. The input data include latitude, longitude, elevation, and the time zone, which allows the calculation of the Sun's position on any day of the year [10]. The most relevant meteorological data used as inputs include air temperature, relative humidity, air pressure, direct and diffuse solar radiation, cloudiness, wind direction and speed, as well as auxiliary precipitation data [10].

EnergyPlus simulation software was previously used for sunspace studies by Chiesa et al. to determine the influence of sunspaces on the reduction of energy demand for heating for different climate conditions of the examined locations in Europe [11]. Ulpiani et al. used EnergyPlus to investigate energy consumption of a residential building with an integrated sunspace in the Mediterranean climate [12]. EnergyPlus was also used to simulate energy consumption in studies of shape factors in high-rise office and public buildings [13-16] as well as in individual residential buildings [17].

3.2. Description of the analyzed models of buildings with a sunspace

Three MODELS of a residential building with a passive sunspace system (Figure 2) were developed. They were used to determine the total energy required for heating and cooling, energy only for heating, and energy only for cooling, depending on the building shape factor, floor geometry, southern façade surface area, and different WWRs.

The first building MODEL (MODEL-I, Fig. 2) has only the ground floor G and the floor area P_o = 92.16 m^2. The second building MODEL (MODEL-II, Fig. 2) has the ground floor G and the floor area P_o=184.32m^2, while the third analyzed MODEL (MODEL-III, Fig. 2) has the ground floor G, the 1st floor (+1) and the area P_o=184.32m^2. The overview of the MODELS (Figure 2) indicates that the area of the second and third MODEL building is double the area of the first MODEL building. The models were set up this way so that it would be possible to determine the effect of the length and surface area of the southern façade containing the sunspace in relation to the heating and cooling energy required for proper functioning of the building. The floor area of the third MODEL building is the same as the second, only over two storey levels (P+1) instead of one. The height of a storey is uniform for all models (H=3m). The volume of MODEL-I is V_1=276 m^3, while the volume of MODEL-II and MODEL-III is V_2=552 m^3.



	D1	C1	B1	A	B2	C2	D2
Aspect ratio	1:2.25	1:1.56	1:1.26	1:1	1.26:1	1.56:1	2.25:1
S (m^2)	309.12	302.4	300.3	299.52	300.3	302.4	309.12
f_o	1.12	1.09	1.087	1.083	1.087	1.09	1.12
MODEL I number of storeys: G P_0=92.16 m^2 H=3m V_1=276.48 m^3							
S (m^2)	542.1	536.37	532.62	531.46	532.62	536.37	542.1
f_o	0.98	0.97	0.963	0.96	0.963	0.97	0.98
MODEL II P_0=184.32 m^2 number of storeys: 2xG H=3m V_2=552.96 m^3							
S (m^2)	433.32	420.48	416.28	414.72	416.28	420.48	433.32
f_o	0.78	0.76	0.753	0.75	0.753	0.76	0.78
MODEL III number of storeys: G+1 P_0=184.32 m^2 H=6m V_2=552.96 m^3							

Fig. 2 Overview of the analyzed models of a residential building with a passive sunspace (MODEL-I, MODEL-II, and MODEL-III)

Residential building with a passive sunspace and square- and rectangle-shaped floors were analyzed (Figure 2). The starting MODEL is MODEL-A with a square floor and the aspect ratio 1:1. This MODEL was used as a reference because it has the lowest shape factor: for MODEL-IA the shape factor is 1.083; for MODEL-IIA the shape factor is 0.96; and for MODEL-IIIA the shape factor is 0.75. Changes in the floor aspect ratio of MODEL-A yielded the variants B, C, and D. Variant B has the aspect ratio 1.26:1, variant C 1.56:1, and variant D 2.25:1 (Figure 2). Variants B, C, and D were used to create their sub-variants B1 and B2, C1 and C2, and D1 and D2. With variants B1, C1, and D1, the shorter side of the building containing a sunspace is facing south. Variants B2, C2, and D2 are facing south with their longer side, which contains the sunspace (Figure 2). For all models considered, the sunspace dimensions are uniform – 6.0x2.4 m. The effect of glazing on the amount of energy required for heating and cooling was analyzed for different WWRs of all façades, specifically WWR=20%, WWR=40%, and WWR=60%.

During the definition of the starting models of buildings with a sunspace, the elements of the thermal envelope were also defined, as they are typical constructions used in Serbia, which has a humid continental climate. Thermal envelope heat transfer coefficient values are defined in terms of maximum allowed values provided in the Rulebook on Energy Efficiency of Buildings in Serbia [18], which pertains to the new residential buildings. Table 1 shows the calculated and maximum values of coefficient **U** for façade walls, flooring and roofing, and windows of all the analyzed MODELS of single residential buildings with a passive sunspace.

Table 1 Calculated and maximum values of coefficient U for the designated elements of the building's thermal envelope

Construction type	Structural assembly elements	U [W/m^{2}K]	U_{max} [W/m^{2}K]
Façade walls	mortar 2cm, brick wall 25cm, thermal insulation 10cm, mortar 1cm	0.29	0.30
Floor	parquet flooring 2.2 cm, cement screed 3cm, thermal insulation 10cm, hydro insulation, lean concrete 10cm, gravel 10cm	0.28	0.30
Flat roof	Cement screed 4cm, hydro insulation, thermal insulation 15cm, sloping concrete 5cm, thermal insulation 7cm, RC slab 14cm, mortar 2cm	0.15	0.15
Glazing	Double glazed, PVC	1.50	1.50

The glazing of the passive sunspace used in this study is the same as the glazing of the thermal envelope. Windows are double glazed with low emissivity glazing of 6/13 mm and framed with PVC material. Heat transfer coefficient for glazing is U=1.5 [W/m^{2}K]. The total solar transmission of the glazing is SHGC=0.568.

4. Results

Annual energy required for heating and cooling and the total annual energy required for heating and cooling were calculated for the defined models (MODEL I, MODEL II, MODEL III) of a residential building with a passive sunspace and their variants with different floor aspect ratios and window-to-wall ratios WWR=20%, WWR=40%, and WWR=60%. The results are shown in Table 2.

Table 2 Annual amount of energy required for heating, cooling, and both heating and cooling of the analyzed models of residential building with a passive sunspace (MODEL-I, MODEL-II, and MODEL-III) for window-to-wall ratios WWR=20%, WWR=40%, and WWR=60%.

	D1	**C1**	**B1**	**A**	**B2**	**C2**	**D2**
Floor aspect ratio	1:2.25	1:1.56	1:1.26	1:1	1.26:1	1.56:1	2.25:1
sf (shape factor)	1.12	1.09	1.087	1.083	1.087	1.09	1.12
MODEL-I WWR=20%							
Annual energy required for heating (kWh)	3498.06	3496.95	3490.54	3473.49	3455.81	3462.16	**3448.31**
Annual energy required for cooling (kWh)	3708.2	3261.26	3083.53	2981.45	2874.84	**2832.82**	2840.8
Annual energy required for heating and cooling (kWh)	7206.26	6758.21	6574.07	6454.94	6330.65	6294.98	**6289.11**
MODEL-I WWR=40%							
Annual energy required for heating (kWh)	3358.48	3368.54	3360.28	3343.47	3315.77	3309.32	**3265.64**
Annual energy required for cooling (kWh)	6441.05	5624.03	5293.9	5070.16	4876.48	**4803.33**	4827.25
Annual energy required for heating and cooling(kWh)	9799.53	8992.57	8654.18	8413.63	8192.25	8112.65	**8092.89**
MODEL-I WWR=60%							
Annual energy required for heating (kWh)	3306.61	3309.39	3291.49	3263.85	3232.9	3218.72	**3172.34**
Annual energy required for cooling (kWh)	9027.42	7871.52	7423.1	7091.43	6813.07	**6704.64**	6720.35
Annual energy required for heating and cooling (kWh)	12334	11180.9	10714.6	10355.3	10046	9923.36	**9892.69**
sf (shape factor)	**0.98**	**0.97**	**0.963**	**0.96**	**0.963**	**0.97**	**0.98**
MODEL-II WWR=20%							
Annual energy required for heating (kWh)	6918.13	6892.7	6853.48	6851.42	6771.24	6757.13	**6684.21**
Annual energy required for cooling (kWh)	3766.18	3319.6	3175.56	3028.51	2928.08	**2873.04**	2921.9
Annual energy required for heating and cooling (kWh)	10684.3	10212.3	10029	9879.93	9699.32	9630.17	**9606.11**
MODEL-II WWR=40%							
Annual energy required for heating (kWh)	6537.7	6504.43	6450.39	6426.62	6329	6295.03	**6173.07**
Annual energy required for cooling (kWh)	7678.33	6683.06	6326.12	6009.27	5792.13	**5696.8**	5816.63
Annual energy required for heating and cooling (kWh)	14216	13187.5	12776.5	12435.9	12121.1	11991.8	**11989.7**
MODEL-II WWR=60%							
Annual energy required for heating (kWh)	6304	6245.45	6193.06	6154.6	6047.28	5995.62	**5857.41**
Annual energy required for cooling (kWh)	11721.9	10281	9716.99	9234.22	8891.05	**8758.43**	8924.38
Annual energy required for heating and cooling (kWh)	18025.9	16526.5	15910.1	15388.8	14938.3	14754.1	**14781.8**
sf (shape factor)	**0.78**	**0.76**	**0.753**	**0.75**	**0.753**	**0.76**	**0.78**
MODEL-III WWR=20%							
Annual energy required for heating (kWh)	6799.06	6744.28	6711.93	6661.2	6627.89	6629.77	**6597.19**
Annual energy required for cooling (kWh)	6419.49	5607.14	5269.79	5098.2	4867.63	**4787.63**	4805.16
Annual energy required for heating and cooling(kWh)	13218.6	12351.4	11981.7	11759.4	11495.5	11417.4	**11402.4**
MODEL-III WWR=40%							
Annual energy required for heating (kWh)	6303.98	6236.4	6189.14	6125.15	6066.17	6043.57	**5971.65**
Annual energy required for cooling (kWh)	12598.4	11078.3	10445.1	10033.5	9640.26	**9511.49**	9593.39
Annual energy required for heating and cooling(kWh)	18902.4	17314.7	16634.3	16158.7	15706.4	**15555.1**	15565
MODEL-III WWR=60%							
Annual energy required for heating (kWh)	6103.1	6011.36	5948.32	5872.95	5801.69	5775.3	**5708.98**
Annual energy required for cooling (kWh)	18397.2	16265	15399.5	14787.7	14240.6	**14066.8**	14183.3
Annual energy required for heating and cooling (kWh)	24500.3	22276.3	21347.9	20660.6	20042.3	**19842.1**	19892.3

Figure 3 shows a diagram of the energy required for heating and cooling of the analyzed models of residential building with a passive sunspace for MODEL-I for WWR=20%, WWR=40%, and WWR=60%.

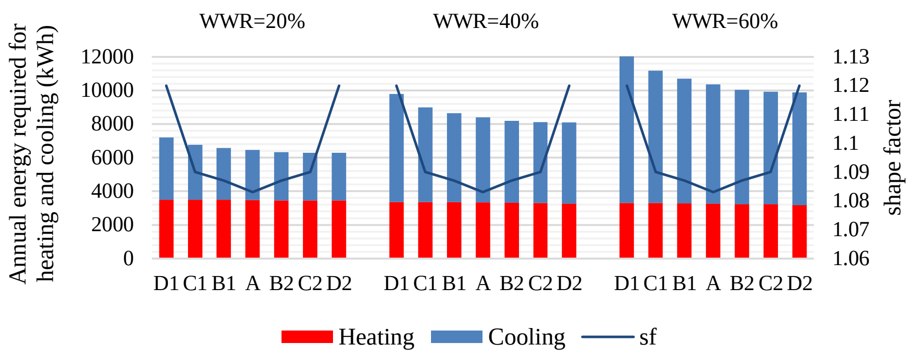


Fig. 3 Annual energy required for heating and cooling for MODEL-I variants and window-to-wall ratios WWR=20%, WWR=40%, and WWR=60%

Table 3 shows the percentages of the increase/decrease of required amount of energy for heating and cooling of the analyzed models of residential building with a passive sunspace for MODEL-I for WWR=20%, WWR=40%, and WWR=60%, in relation to the referential MODEL-A.

Table 3 Percentage of increase (+) and decrease (–) of the total energy required for heating and cooling of a building with a sunspace for MODEL-I

MODEL-I	WWR 20%						
Percentage of the change of required energy	Floor geometry sub-variants						
	D1	C1	B1	A	B2	C2	D2
Change of energy required for heating	+0.71%	+0.68%	+0.49%	ref	–0.51%	–0.33%	–0.72%
Change of energy required for cooling	+24.38%	+9.39%	+3.42%	ref	–3.58%	–4.99%	–4.72%
Change of total energy required for heating and cooling	+11.64%	+4.70%	+1.85%	ref	–1.93%	–2.48%	–2.57%
MODEL-I	WWR 40%						
Percentage of the change of required energy	Floor geometry sub-variants						
	D1	C1	B1	A	B2	C2	D2
Change of energy required for heating	+0.45%	+0.75%	+0.50%	ref	–0.83%	–1.02%	–2.33%
Change of energy required for cooling	+27.04%	+10.92%	+4.41%	ref	–3.82%	–5.26%	–4.79%
Change of total energy required for heating and cooling	+16.47%	+6.88%	+2.86%	ref	–2.63%	–3.58%	–3.81%
MODEL-I	WWR 60%						
Percentage of the change of required energy	Floor geometry sub-variants						
	D1	C1	B1	A	B2	C2	D2
Change of energy required for heating	+1.31%	+1.40%	+0.85	ref	–0.95%	–1.38%	–2.80%
Change of energy required for cooling	+27.30%	+11.00%	+4.68%	ref	–3.93%	–5.45%	–5.23%
Change of total energy required for heating and cooling	+19.11%	+7.97%	+3.47%	ref	–2.99%	–4.17%	–4.47%

Figure 4 shows a diagram of the energy required for heating and cooling of the analyzed models of residential building with a passive sunspace for MODEL-II for WWR=20%, WWR=40%, and WWR=60%.

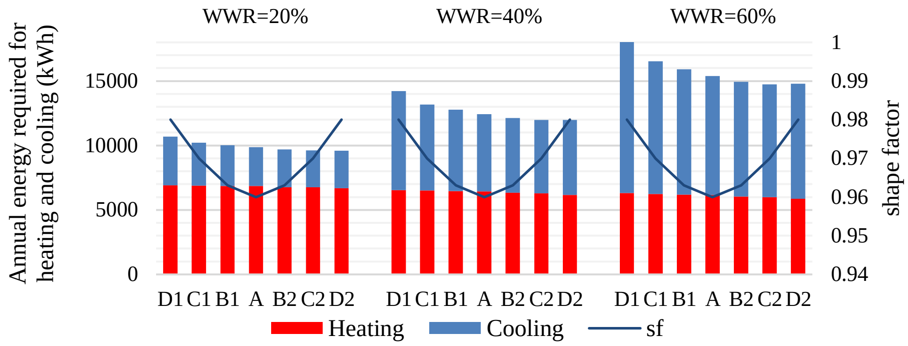


Fig. 4 Annual energy required for heating and cooling for MODEL-II variants and window-to-wall ratios WWR=20%, WWR=40%, and WWR=60%

Table 4 shows the percentages of the increase/decrease of required amount of energy for heating and cooling of the analyzed models of residential building with a passive sunspace for MODEL-II for WWR=20%, WWR=40%, and WWR=60%.

Table 4 Percentage of increase (+) and decrease (–) of the total energy required for heating and cooling of a building with a sunspace for MODEL-II

MODEL-II	WWR 20%						
Percentage of the change of required energy	Floor geometry sub-variants						
	D1	C1	B1	A	B2	C2	D2
Change of energy required for heating	+0.97%	+0.60%	+0.03%	ref	–1.17%	–1.38%	–2.44%
Change of energy required for cooling	+24.36%	+9.61%	+4.86%	ref	–3.32%	–5.13%	–3.52%
Change of energy required for heating and cooling	+8.14%	+3.36%	+1.51%	ref	–1.83%	–2.53%	–2.77%
MODEL-II	WWR 40%						
Percentage of the change of required energy	Floor geometry sub-variants						
	D1	C1	B1	A	B2	C2	D2
Change of energy required for heating	+1.73%	+1.21%	+0.37%	ref	–1.52%	–2.05%	–3.95%
Change of energy required for cooling	+27.77%	+11.21%	+5.27%	ref	–3.61%	–5.20%	–3.21%
Change of energy required for heating and cooling	+14.31%	+6.04%	+2.74%	ref	–2.53%	–3.57%	–3.59%
MODEL-II	WWR 60%						
Percentage of the change of required energy	Floor geometry sub-variants						
	D1	C1	B1	A	B2	C2	D2
Change of energy required for heating	+2.43%	+1.48%	+0.62%	ref	–1.74%	–2.58%	–4.83%
Change of energy required for cooling	+26.94%	+11.34%	+5.23%	ref	–3.72%	–5.15%	–3.36%
Change of energy required for heating and cooling	+17.14%	+7.39%	+3.39%	ref	–2.93%	–4.12%	–3.94%

Figure 5 shows a diagram of the energy required for heating and cooling of the analyzed models of residential building with a passive sunspace for MODEL-III for WWR=20%, WWR=40%, and WWR=60%.

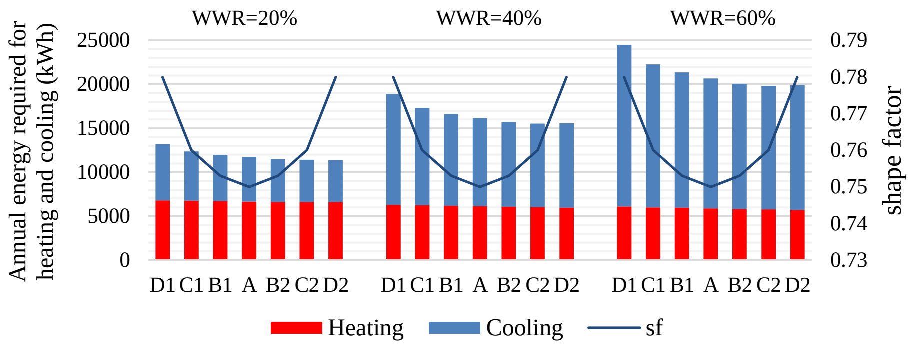


Fig. 5 Annual energy required for heating and cooling for MODEL-III variants and window-to-wall ratios WWR=20%, WWR=40%, and WWR=60%

Table 5 shows the percentages of the increase/decrease of required amount of energy for heating and cooling of the analyzed models of residential building with a passive sunspace for MODEL-III for WWR=20%, WWR=40%, and WWR=60.

Table 5 Percentage of increase (+) and decrease (–) of the total energy required for heating and cooling of a building with a sunspace for MODEL-III

MODEL-III	WWR 20%						
Percentage of the change of required energy	Floor geometry sub-variants						
	D1	C1	B1	A	B2	C2	D2
Change of energy required for heating	+2.07%	+1.25%	+0.76%	ref.	–0.50%	–0.47%	–0.96%
Change of energy required for cooling	+25.92%	+9.98%	+3.37%	ref	–4.52%	–6.09%	–5.75%
Change of energy required for heating and cooling	+12.41%	+5.03%	+1.89%	ref	–2.24%	–2.91%	–3.04%
MODEL-III	WWR 40%						
Percentage of the change of required energy	Floor geometry sub-variants						
	D1	C1	B1	A	B2	C2	D2
Change of energy required for heating	+2.92%	+1.82%	+1.04%	ref	–0.96%	–1.33%	–2.51%
Change of energy required for cooling	+25.56%	+10.41 %	+4.10%	ref	–3.92%	–5.20%	–4.39%
Change of energy required for heating and cooling	+16.98%	+7.15%	+2.94%	ref	–2.80%	–3.74%	–3.67%
MODEL-III	WWR 60%						
Percentage of the change of required energy	Floor geometry sub-variants						
	D1	C1	B1	A	B2	C2	D2
Change of energy required for heating	+3.92%	+2.36%	+1.28%	ref	–1.21%	–1.66%	–2.79%
Change of energy required for cooling	+24.41%	+9.99%	+4.14%	ref	–3.70%	–4.87%	–4.09%
Change of energy required for heating and cooling	+18.58%	+7.82%	+3.33%	ref	–2.99%	–3.96%	–3.72%

5. Discussion

When designing residential buildings with a passive sunspace system that use the available solar energy for heating, it is necessary to know the Sun's position and the angle of incidence of solar rays depending on the time of year. In humid continental climate conditions of the city of Niš and in relation to its geographic location (43.3209° N, 21.8958° E), during the summer the Sun rises from the northeast, travels high across the south, and sets in the northwest. During the winter, it rises from the southeast and arcs at a low angle of incidence across the south to set in the southwest. This means that the increase of the exposed surface of the southern façade provides higher efficiency of solar radiation during the winter months, whereas the decrease of the exposed surface of the eastern and western façades reduces overheating in the summer. During the summer, especially in the afternoon, the western façade tends to overheat. On the other hand, the building envelope enables heat exchange between the internal and the external space, whereby it is important to make as few transmission losses as possible through the building envelope while maintaining the maximum heat gain of the passive sunspace in the winter and the minimum heat gain in the summer.

According to the results provided in Table 3 for the analyzed sub-variants of MODEL-I and for the listed window-to-wall ratios (WWR=20%, WWR=40%, WWR=60%), it can be concluded that, in terms of energy required for heating, MODEL-I D2 is the most favourable, while MODEL-I C2 is the most favourable in terms of energy required for cooling. When a comparison of the energy required for heating with WWR=20% is made between MODEL-I D1, whose shorter side is facing south, and MODEL-I D2, whose longer side is facing south, with the same building shape factor, the amount of energy required for heating will be higher by 1.43% in MODEL-I D1. The amount of energy required for cooling in MODEL-I D1 is higher by 29.1% compared to MODEL-I D2, under the same conditions. The calculated total annual energy required for heating and cooling in MODEL-I D1 is 14.21% higher than in MODEL-I D2 (Table 3); with WWR=40%, between the respective MODELS, the total annual energy required for heating and cooling is 20.28% higher. In case of WWR=60%, the total annual energy required for heating and cooling would be higher by 23.58%.

Based on the results for the analyzed sub-variants of MODEL-II and for the listed window-to-wall ratios (WWR=20%, WWR=40%, WWR=60%) provided in Table 4, it can be concluded that, in terms of energy required for heating, MODEL-II D2 is the most favourable, while MODEL-II C2 is the most favourable in terms of energy required for cooling. When a comparison of the energy required for heating with WWR=20% is made between MODEL-II D1, whose shorter side is facing south, and MODEL-II D2, whose longer side is facing south, with the same building shape factor, the amount of energy required for heating will be higher by 3.41% in MODEL-II D1. The amount of energy required for cooling in MODEL-II D1 is higher by 27.88% compared to MODEL-II D2, under the same conditions. The calculated total annual energy required for heating and cooling in MODEL-II D1 is 10.91% higher than in MODEL-II D2 (Table 4); with WWR=40%, between the respective MODELS, the total annual energy required for heating and cooling is 17.9% higher. In case of WWR=60%, the total annual energy required for heating and cooling would be higher by 21.08%.

When a comparison of the energy required for heating with WWR=20% is made between MODEL-III D1, whose shorter side is facing south, and MODEL-III D2, whose longer side is facing south, with the same building shape factor, the amount of energy required for heating will be higher by 3.03% in MODEL-III D1. The amount of energy required for cooling in MODEL-III D1 is higher by 31.67% compared to MODEL-III D2, under the same conditions. The calculated total annual energy required for heating and cooling in MODEL-III D1 is 15.45% higher than in MODEL-III D2 (Table 5); with WWR=40%, between the respective MODELS, the total annual energy required for heating and cooling is 20.65% higher. In case of WWR=60%, the total annual energy required for heating and cooling would be higher by 22.3%.

These results lead to a conclusion that there is no simple linear dependency between the WWR and the increase percentage of the total annual energy required for heating and cooling. Another conclusion is that the increase of total energy consumption is the result of a considerable increase of the energy required for cooling (Figure 3-5).

Based on the results presented above, it can be observed that the least energy required for heating of a building with a sunspace was found for a building with the largest southern façade area for the biggest WWR. This can be related to the angle of incidence of solar radiation typical for the winter period, when the solar exposure time of the southern façade is longer than that of other façades, which provides the better passive heating of the building. For the same reason, the solar exposure time of the southern façade is shorter during the summer compared to the eastern and western façades. The analysis of the same shape factor of the building, while taking into account the cooling requirements in the summer, leads to a conclusion that it is more favourable to have a larger surface area of the southern façade at the same given sunspace size. The maximum savings in the annual energy required for heating and cooling of the analyzed residential building with a passive sunspace, possible through southern orientation of the longer side of the building, amount to 23.58%, 21.08%, and 22.3% for MODEL-I, MODEL- II, and MODEL-III, respectively.

In the building design stage, insufficient knowledge of the influence of building shape, orientation, and WWR on energy consumption in the summer or in the winter can result in later disadvantages, which are only partially rectifiable after the construction is completed and the building goes into use. The results presented in this paper can help achieve better energy efficiency of buildings depending on the floor aspect ratio, defined in the initial design stages, and on the WWR, which, in addition to the passive sunspace, allows direct passage of sunlight.

6. Conclusion

This paper considered the amount of energy required for heating and cooling of single building with a passive sunspace for different floor geometry, southern façade surface area, shape factor, and three window-to-wall ratios: WWR=20%, WWR=40%, and WWR=60%. Three building MODELS were analyzed: MODEL-I (number of storeys G and floor area P_o= 92.16 m^2), MODEL-II (number of storeys G and floor area P_o= 184.32 m^2), and MODEL-III (number of storeys G+1 and floor area P_o= 184.32 m^2).

The results indicated that, in terms of the amount of energy required for heating, MODEL-I D2, MODEL-II D2, and MODEL-III D2 were the most favourable. The D2 sub-variant for all MODELS has the same aspect ratio of 2.25:1 and the longer side of its façade, where the sunspace is installed, is facing south. In terms of the amount of energy required for cooling, MODEL-I C2, MODEL-II C2, and MODEL-III C2 were the most favourable. The C2 sub-variant for all MODELS has the same aspect ratio of 1.56:1 and the longer side of its façade, where the sunspace is installed, is facing south.

Upon analysis of the aforementioned MODELS of residential building with a passive sunspace, it was concluded that there is no direct proportional dependency between the building shape factor and the total amount of energy required for heating and cooling. As the WWR increases, so does the amount of energy required for cooling, whereas the amount of energy required for heating slightly decreases under the same conditions. In building models with a higher WWR, the required amount of energy required for cooling is larger than the amount of energy required for heating, so its share in the total energy consumption also increases.

Adequate sizing of the south-facing façade can significantly reduce the amount of energy required for heating and cooling. In buildings with the same shape factor and WWR, savings in total energy consumption for heating and cooling can be as much as 23% higher when the longer façade of the building is facing south. The paper examined the window-to-wall ratios of WWR=20%, WWR=40%, and WWR=60% for all façades. A recommendation for further research is to define the window-to-wall ratio individually in relation to façade orientation. This would determine the optimal window-to-wall ratio of the southern façade in relation to the eastern, western, and northern ones. The results presented in this study can be used as recommendations in the design of residential buildings with a sunspace.

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UTICAJ GEOMETRIJE STAMBENOG OBJEKTA SA STAKLENOM VERANDOM NA NJEGOVE ENERGETSKE PERFORMANSE

Porast potrošnje energije u sektoru zgradarstva i problemi koji se odnose na zaštitu životne sredine, usmerili su mnoga aktuelna istraživanja na smanjenje ukupne emisije CO_2, što je u sektoru zgradarstva uslovilo formiranje različitih mera za povećanje energetske efikasnosti. Jedna od mera za ostvarivanje ušteda i racionalno korišćenje energetskih resursa kod individualnih stambenih obejakat je i primena pasivnih solarnih sistema sa staklenom verandom. U radu je prikazan uticaj faktora oblika stambene zgrade sa pasivnim sistemom staklenom verandom na ukupnu potrošnju energije za grejanje i hlađenje. Proračun ukupne potrebne energije za grejanje i hlađenje zgrade izvršen je dinamičkim modelovanjem pomoću softverskog paketa Energy Plus. Prilikom sprovođenja simulacija, korišćeni su meteorološki parametri za područje grada Niša. Formirani su modeli stambenog objekta sa pasivnim sistemom staklenom verandom kvadratne i pravougaone osnove. Varijacije u modelima obuhvataju različit faktor oblika zgrade kao i geometriju osnove zgrade, površinu južne fasade objekta i procenat ostakljenja. Rezultati istraživanja modela sa procentom ostakljenja WWR=20%, WWR=40%, WWR=60% pokazuju da je izdužena forma zgrade sa odnosom stranica 2.25:1 gde je duža strana fasade okrenuta ka jugu, najpovoljnija sa aspekta potrošnje energije za grejanje. Za iste procente ostakljenja najpovoljniji odnos stranica osnove sa aspekta potrošnje energije za hlađenje je izdužena forma zgrade sa odnosom stranica 1.56:1 gde je duža strana fasade okrenuta ka jugu. Sa povećanjem procenta ostakljenja raste i potrebna energija za hlađenje zgrade. Najveći porast u potrošnji energije za grejanje je kod objekata sa odnosom stranica 1:2.25 koji su kraćom stranom okrenuti ka jugu.

Ključne reči: *pasivni sistemi, staklena veranda, stambena zgrada, energetska efikasnost*