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DYNAMIC ENERGY SIMULATION OF A BUILDING BEFORE AND AFTER THE APPLICATION OF FAÇADE NANOMATERIALS

The architecture of Modernism in Skopje represent an important cultural heritage of the city. Those buildings were built in lack of thermal insulation materials and have very poor thermal properties. In order to improve their energy efficiency and thermal comfort, numerous of inappropriate interventions are made daily. In this paper, a dynamic software simulation of the energy performance of a Modernist building is made, in order to see the real energy condition of the building and also its possible improvements by using nanomaterials on the façade walls, which has minimal impact on their authentic appearance. The application of aerogel thermal plaster is suggested as scenario 1, and the application of nano ceramic coating as scenario 2. The following parameters are analyzed and discussed: energy consumption for heating, electricity consumption, CO_2 emission, thermal comfort and financial costs by comparing the two scenarios with the current situation. From the simulations it can be concluded that scenario 1 gives better results in terms of energy efficiency, but scenario 2 has smaller impact of the authenticity of the building.

DINAMIČKA ENERGETSKA SIMULACIJA ZGRADE PRE I POSLE PRIMENE FASADNIH NANOMATERIJALA

Modernistička arhitektura u Skoplju predstavlja značajno kulturno nasleđe grada. Ti objekti su izgrađeni u nedostatku termoizolacionih materijala i njihova termička svojstva su veoma slaba. U cilju poboljšanja njihove energetske efikasnosti i toplotnog komfora svakodnevno se vrše brojne neodgovarajuće intervencije. U ovom radu je urađena dinamička softverska simulacija energetskih performansi modernističke zgrade, kako bi se sagledalo stvarno energetsko stanje zgrade, kao i njena moguća poboljšanja korišćenjem nanomaterijala na fasadnim zidovima, što ima minimalan uticaj na njihov autentični izgled. Primena aerogel termo maltera je predložena kao scenario 1, a primena nano keramičkog premaza kao scenario 2. Analiziraju se i razmatraju sledeći parametri: potrošnja energije za grejanje, potrošnja električne energije, emisija CO_2, toplotni komfor i finansijski troškovi poređenjem ova dva scenarija sa trenutnom situacijom. Iz simulacije se može zaključiti da scenario 1 daje bolje rezultate u pogledu energetske efikasnosti i toplotne udobnosti, ali scenario 2 ima manji uticaj na autentičnost zgrade.

Ključne reči: energetska efikasnost, nanomaterijali, dinamička energetska simulacija, modernizam

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1. INTRODUCTION

The architecture of 20th century, known as Modernist architecture, represents an important cultural heritage for the City of Skopje. [1] According to the construction standards of that time, the buildings were built in the absence of thermal insulation materails [2], which resulted in bad thermal comfort, high costs for heating, cooling and maintenance, degradation and decay. Those building need to be properly renovated according to today's energy efficiency standards. [3] [4] On the other hand, according to [5], the architecture that is considered as a cultural heritage must not undergo changes that would change its authentic appearance. In order to solve the problem with the energy efficiency and thermal confort in Modernist buildings, and in the same time to minimaze the impact on their authensity after the renovation process, two types of facade nanomaterials are analysed. In this paper, a dynamic software simulation of the existing state of a selected Modernist building is made, and the analyzed materials are used as improved scenarios. The application of aerogel based thermal plaster on the facade walls is defined as scenario 1, while the application of nano ceramic coating is defined as scenario 2. The selected ''case study'' is a Modernist building, considered as cultural hertage, which facade is designed entirely in natural concrete, known as "beton-brut“(Fig.1).



a) b) c)

Figure 1 – Modernist building complex - student dormitory in Skopje a) Whole complex of the four blocks - front view b) Case study block “B” – front view c) Case study “block - B”- entry view

2. SELECTING FACADE NANOMATERIALS

The State of the art of nanomaterials in the building sector was first investigated, especially in terms of energy efficiency. Additional complication of the research problem is the factor of preservation of the authentic appearance of the building which leads to an extensive research process, where through a detailed systematic review of the scientific literature, a selection of the most appropriate nanomaterials has been made to improve energy efficiency, sustainability, and also protect the authenticity of buildings. From all the researched nanomaterials two types of nanomaterials were chosen for the simulation: thermal plaster based on nano silica aerogel and thermal coating based on nano ceramic microspheres. Both materials have their advantages and disadvantages, however, compared to other analyzed materials, they are estimated to be the most appropriate in solving the problem and creating minimal impact based on the following established criteria: thermal conductivity, toxicity and environment damage, cultural heritage protection and thickness).

The research showed that aerogel based thermal plaster has a low coefficient of thermal conductivity λ ranging from 0.028-0.014W/mK [6], thanks to the porous nano structure. [7] In the buildings renovated with this type of plaster, energy savings could be over 50% [8]. According to the criteria for protection of cultural heritage (authenticity, integrity, reversibility and compatibility) aerogel plasters have a moderate impact on the authenticity of buildings, but it is important that they are compatible with the chemical composition of the original materials, which can be easily removed

without damaging them and there is no need for additional fastening that would damage the original material. [9] They have great flexibility in applying uneven surfaces, architectural details and insulating thermal bridges [6] [10]. Due to the composition and method of application, aerogel plasters perfectly mimic the texture of natural concrete and it is difficult to distinguish (Fig. 2), while the original material remains preserved under the mortar. The cost of the aerogel is still high, which prevents its intense spread in construction [11].

The nano coating has an indeterminate coefficient of thermal conductivity λ, which can be roughly calculated or measured on the building itself after application. From the studied literature, λ varies around 0.001-0.003 W/mK [12]. The nano coating has an extremely small thickness of 0.0003 m, and therefore the coefficient λ does not play the main role, but the processes of many complex mechanisms in the nano structure of the coating, which are included in the so called factor f_{TS} [13]. Based on the mechanisms of action, the f_{TS} factor varies and is different for each material. Through several laboratory experiments and *in situ* measurements, a calculation software (Calculus) for calculating the f_{TS} factor for different coating materials has been developed [14]. Based on the measurements of buildings renovated with nano ceramic coating, energy savings can be up to 30% [15]. In terms of cultural heritage preservation, the nano coating corresponds very well to the set criteria, without impacting the authentic appearance, thanks to its transparency. (Fig. 2) The cost of the nano coating is lower than aerogel plaster, but higher than conventional coatings and paints [16].



a) b) c) d)

Figure 2 – Original materials vs. nanomaterials application a) Exposed rough concrete wall b) Wall with applied aerogel plaster as imitation of rough concrete c) Aacrylic plaster finished wall [16] d) Same wall after the application of nano ceramic coating [16]

3. ENERGY SIMULAITION AND RESULTS

3.1. Methodology

A dynamic software simulation of the energy performance of case study building which is student dormitory (Fig. 2) is made using BIM integrated soft wares Energy Plus and Open Studio. The dormitory has a complex plan of four equal towers. In this paper, only one tower, named as “block - B" is analyzed. Fig. 8 shows the characteristic floor plan and its division into five thermal zones. The building is zoned into a total of 62 thermal zones. The project temperature for the stair’s zones is 20°, for the room’s 21°, for the toilet’s 24° and in the basement 15°. The block has net area of 5 520 m² and net volume 15 346 m³, a heated area of 5 002 m² and a heating volume of 13 792 m³ with a capacity of 304 tenants. The glazed area of the facade is 1 268 m². The building is supplied with heat through district heating network (130/70° water) and stored in a thermal substation with a capacity of 578 980 kcal/h. It is distributed through a central hot water pump with forced circulation to the radiators in each zone. Sanitary hot water is prepared from a boiler with a capacity of 4 000l, with combined heaters. The cooling and ventilation of the building are natural, except for the bathrooms in the rooms, where the ventilation is mechanical. The building is heated from 15th of October till 15th of April. Climate data are read simultaneously by the Hydro meteorological Institute in Skopje, which enables accurate calculations in real non-stationary conditions.

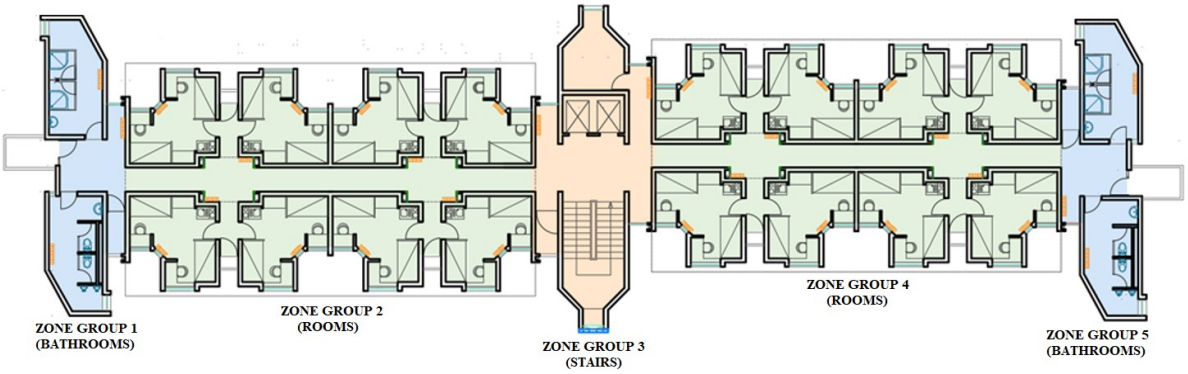


Figure 2 – Characteristic floorplan of the selected building and thermal zones division

Table 1 shows the materials of the building envelope and their thermal properties of the current situation and the added materials and their properties in scenarios 1 and 2. In the current state the windows are made of aluminum profiles with single glass with U_w = 5.61 W/m^{2}K. In the improved scenarios the windows are made of six chamber aluminum profiles and two layer low emission glass with U_w = 1.2 W/m^{2}K. The nano ceramic coating (Table 1) does not give a specific value of the coefficient λ, but the thermal conductivity is calculated by including the f_{TS} factor for each envelope material. f_{TS} (e.g. f_{TS} for reinforced concrete is 0.55; perlite concrete – 0.40; gypsum mortar – 0.35; ceramic tiles – 0.40). The thermal conductivity for each element of the envelope is calculated in Calculus and the values are then entered into Energy Plus.

Table 1 – Envelope materials properties (current state, scenario 1 and scenario 2)

Envelope	**Material properties**					
	Materials	***λ (W/mK)***	***c (J/kgK)***	***ρ (kg/m³)***	***d (m)***	***μ [-]***
Façade wall type 1 (Current state)	plastic wallpaper	0.2	1250	700	0.002	7000-50000
	gypsum	0.16	830	784.9	0.005	6-10
	perlite concrete	0.25	1000	800	0.04	60-100
	reinfroced concrete	2.6	1000	2500	0.2	80-130
Scenario 1	aerogel plaster	0.028	990	156	0.06	4-5
Scenario 2	ceramic coating	f_{TS}	/	290-410	0.0003	2
Façade wall type 2 (Current state)	ceramic tiles	1.3	840	2300	0.01	200
	perlite concrete	0.25	1000	800	0.04	60-100
	reinfroced concrete	2.6	1000	2500	0.2	80-130
Scenario 1	aerogel plaster	0.028	990	156	0.06	4-5
Scenario 2	ceramic coating	f_{TS}	/	290-410	0.0003	2
Façade wall type 3 (Current state)	gypsum plaster	0.54	1000	1500	0.015	6-10
	reinfroced concrete	2.6	1000	2500	0.2	80-130
Sceanrio 1	aerogel plaster	0.028	990	156	0.06	4-5
Scenario 2	ceramic coating	f_{TS}	/	290-410	0.0003	2
Façade wall type 4 (Current state	reinfroced concrete	2.6	1000	2500	0.2	80-130
Scenario 1	aerogel plaster	0.028	990	156	0.06	4-5
Scenario 2	ceramic coating	f_{TS}	/	290-410	0.0003	2
Ground floor slab structure type 1 (Current state)	carpet	0.08	1230	0.27	0.005	/
	self-leveling mass	1.4	1050	2200	0.035	50-70
	reinfroced concrete	2.6	1000	2500	0.16	80-130
Scenario 1 and 2	eps	0,031	1450	15-40	0,1	60

Envelope	Material properties					
	Materials	***λ (W/mK)***	***c (J/kgK)***	***ρ (kg/m³)***	***d (m)***	***μ [-]***
Ground floor slab structure type 2 (Current state)	ceramic tiles	1.3	840	2300	0.01	200
	cement mortar	1.4	1050	2100	0.04	15-35
	reinforced concrete	2.6	1000	2500	0.16	80-130
Scenario 1 and 2	eps	0,031	1450	15-40	0,1	60
Flat roof type 1 (Current state)	basalt tiles	2	1000	2447	0.04	20-30
	sand	0.58	840	1800	0.02	/
	cement mortar	1.4	1050	2100	0.04	15-35
	vapour barrier	0.16	1460	1121.29	0.0095	100000
	aluminium foil	203	940	2700	0.001	/
	bitumen coating	0.17	1460	1100	0.004	5000
	perlite concrete	0.25	800	1000	0.08	60-100
	glass wool	0.032	840	30	0.04	1-5
	reinforced concrete	2.6	1000	2500	0.08	80-130
Scenario 1 and 2	eps	0,035	1030	10-200	0,2	1-5
	plywood	0.12	1800	1000	0.01	50-70
Flat roof type 2 (Current state)	gravel	0.81	840	1700	0.06	/
	vapour barrier	0.16	1460	1121.29	0.0095	100000
	aluminium foil	203	940	2700	0.001	/
	bitumen coating	0.17	1460	1100	0.004	5000
	perlite concrete	0.25	800	1000	0.08	60-100
	glass wool	0.032	840	30	0.04	1-5
	reinforced concrete	2.6	1000	2500	0.08	80-130
Scenario 1 and 2	eps	0,035	1030	10-200	0,2	1-5
	plywood	0.12	1800	1000	0.01	50-70

The simulation obtained the following results for all three scenarios: heat consumption; electricity consumption for heating; consumption of electricity from electrical appliances and equipment; electricity consumption for lighting; energy consumption for hot sanitary water; CO_2 emissions; indoor air humidity and temperature in each zone; surface internal and external temperatures of the walls; energy losses from infiltration, ventilation, windows and opaque surfaces for each zone; U values of all structural elements of the envelope. The results that show the biggest impact of the applied materials in the improved scenarios are presented in this paper.

3.2. Heating energy consumptions and CO_2 emissions

Energy simulations showed that the building biggest energy consumption is for district heating. In real conditions, the average consumption of energy for heating is 190 kWh hourly, 4 553 kWh daily and 138 478 kWh monthly (Table 2), i.e. 1 661 736 kWh annually. That is 227 kWh/m², which is over 25% higher than the consumption of an average building (170 kWh/m²). Scenario 1 showed a reduction of thermal energy by 52%, i.e. the average consumption is 91 kWh hourly, 2 177 kWh daily and 66 237 kWh monthly (Table 2), i.e. 794 841 kWh annually. That is 109 kWh/m², which is a relatively low consumption for buildings of this type. Scenario 2 showed a decrease of 23%, i.e. the average consumption is 147 kWh hourly, 3 538 kWh daily and 107619 kWh monthly (Table 2), i.e. 1 291 428 kWh annually. That is 176 kWh/m², defining the building in the average consumers. Figure 3 shows the graphic of monthly energy consumption for heating in kWh for the three conditions, where it can be concluded that scenario 1 has the lowest heating energy consumption, which is lower that scenario 2 by 30% and lower than the current state by 50%.

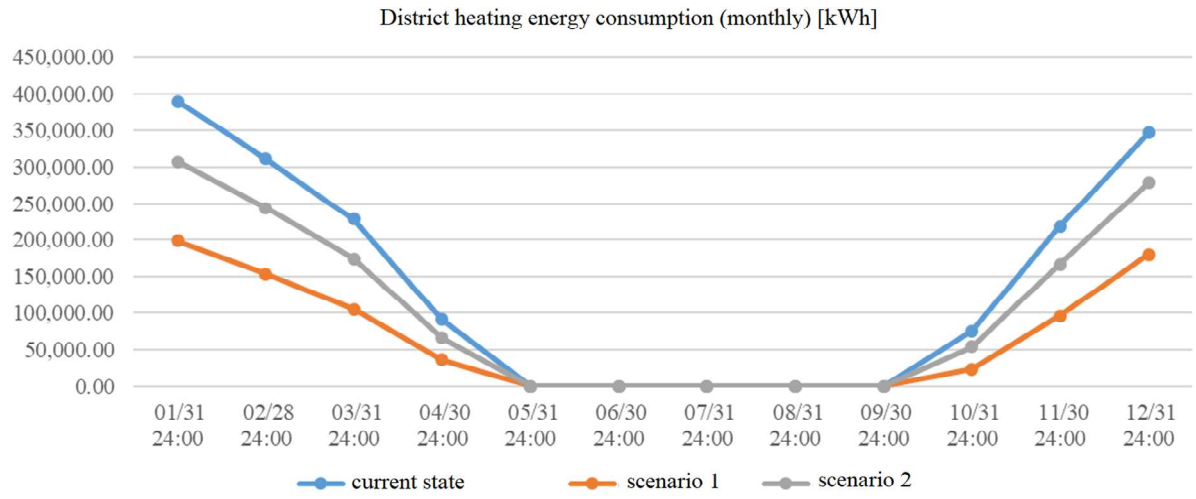


Figure 3 – Comparisons of the district heating energy consumption of the current state and both scenarios

The total electricity consumption of the current situation is 53 kWh hourly, 1 275 kWh daily and 38 796 kWh monthly, i.e. 465 556 kWh annually or 64 kWh/m^2. The total electricity energy consumption is divided into: heating electricity (if the district heating system cannot reach the design temperature, electrical heating is activated); electricity for appliances, hot water and for lighting.

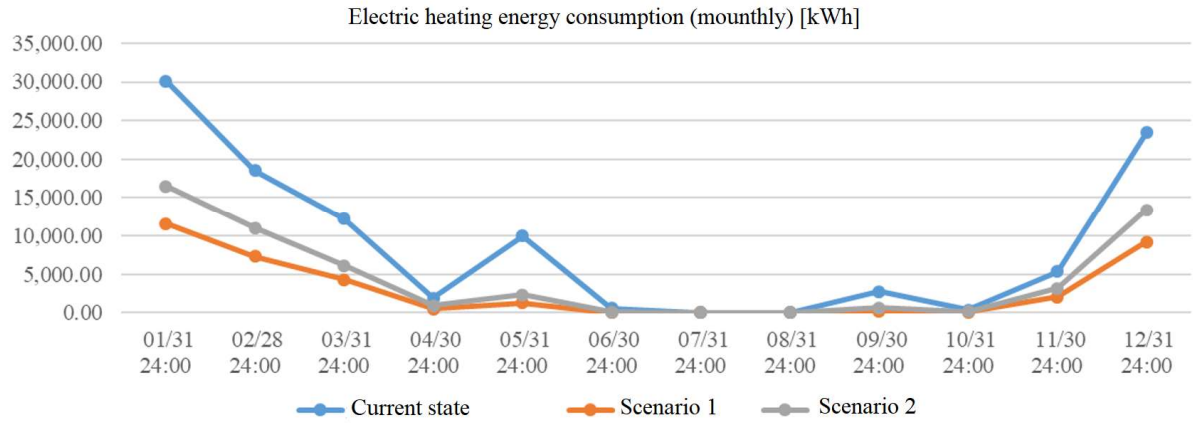


Figure 4 – Comparisons of the electric heating energy consumption of the current state and both scenarios

Table 2 shows the average monthly consumption of different electricity for the current state and both scenarios. The simulations showed that in the improved scenarios only the electricity for heating changes. Electricity consumed for lighting, sanitation and electrical appliances remains the same. In scenario 1 the total average electricity consumption is reduced by 15%, i.e. is 45 kWh hourly, 1 080 kWh daily and 32 875 kWh monthly, i.e. 394 502 kWh per year or 54 kWh/m^2, and in scenario 2 it is 47 kWh hourly, 1 138 kWh daily and 34 624 kWh monthly, i.e. 415 490 kWh annually or 57 kWh/m^2, which is by 11% lower than the existing one (Table 2). The average electricity consumption for heating in the current state is 12 kWh hourly, 288 kWh daily, 8 762 kWh monthly, i.e. additional heating use is 105 144 kWh annually or 14 kWh/m^2. Scenario 1 shows a drastic reduction of heating electricity by 65%, i.e. 4 kWh hourly, 100 kWh daily and 3 036 kWh monthly, i.e. 36 339 kWh annually or 5 kWh/m^2. Scenario 2 showed a reduction by 51%, i.e. 6 kWh hourly, 149 kWh daily and 4,524 kWh monthly, i.e. 54 285 kWh annually or 7 kWh/m^2 (Table 2). Fig. 4 shows the graphics of the monthly electricity consumption, from which can be concluded that scenario 1 has the lowest consumption, i.e. by 33% lower than scenario 2 and by 65% lower than the current state.

The pollution factor is also included in the simulation, i.e. the CO_2 emissions of the building. Fig. 5 shows the graphic of monthly CO_2 emissions that the building releases in the current state and both improved scenarios) In real conditions, the building emits an average of 144 kg of CO_2 hourly, 3 456 kg daily, and 105 125 kg monthly (Table 2). The highest emission of 572 kg hourly was recorded in December. According to the standards, this building has high CO_2 emission, i.e. in winter season the emissions reaches over 500 kg per hour. The average annual CO_2 emission is 1 261 500 kg. If the limit of 500 000 kg per year is exceeded, it is considered as highly polluting facility, which indicates that the building is highly CO_2 emissive.

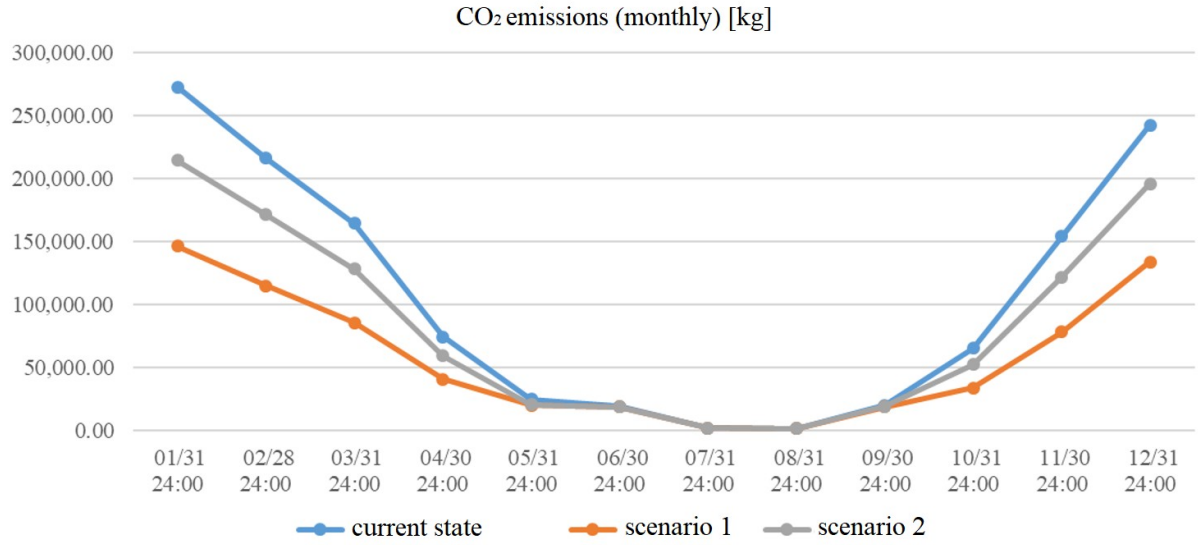


Figure 5 – Comparisons of the monthly CO_2 emissions between the current state and both scenarios

Scenario 1 showed lowest CO_2 emissions with an average of 80 kg hourly, 1 916 kg daily and 58 273 kg monthly, i.e. 699 332 kg annually (Table 2). Emissions in scenario 1 are reduced by 45% compared to the current state. Scenario 2 showed an average emission of 11 kg hourly, 768 kg daily and 84 194 kg monthly, i.e. 1 010 328 kg annually (Table 2). In scenario 2, the emissivity is reduced by 20% compared to the current situation. Fig. 5 shows the graphs of the monthly CO_2 emissions for the three conditions. It can be concluded that scenario 1 has the lowest emissivity with 150 000 kg, scenario 2 with 220 000 kg, and in current state the building emits over 250 000 kg. Scenario 1 has a lower emissivity compared with Scenario 2 by 30% and by 45% compared with the current state.

Table 2 – Average values for heating and electricity energy consumption and CO_2 emissions

Energy consumption and emissions	**Current state**			**Scenario 1**			**Scenario 2**		
	hour	***month***	***year***	***hour***	***month***	***year***	***hour***	***month***	***year***
District heating energy consumption [kWh]	190	4553	138478	91	2177	66237	147	3538	107619
Heating electricty consumption [kWh]	12	288	8762	4	100	3036	6	148	4 524
Sanitary water electricity consumption [kWh]	10	251	763	10	251	7631	10	251	7631
Electricity consumption from appliances [kWh]	21	498	15152	21	498	15152	21	498	15152
Electricity consumption from lightening [kWh]	9	215	6536	9	215	6536	9	215	6536
Total electricity consumption [kWh]	53	1 275	38796	45	1081	32875	47	1138	34624
CO_2 emissions [kg]	144	3 456	105125	80	1916	58273	115	2768	84194

3.3. U values of the envelope

Based on the existing data for the structural element's materials of the building envelope, the U values of the current state are calculated, and after that compared with the optimal recommended U values according to today's Rulebook for energy performances of buildings [20] as well as with the simulated U values in the improved scenarios, shown in Table 3.

Table 3 – U values of the structural elements of the building envelope

Envelope	*U values (current state) [W/m²K]*	*U values (scenario 1) [W/m²K]*	*U values (scenario 2) [W/m²K]*	Max. allowed U values [W/m²K]
Façade wall type 1	2.33	0.38	1.54	0.35
Façade wall type 2	3.93	0.41	2.75	0.35
Façade wall type 3	2.53	0.39	1.66	0.35
Façade wall type 4	4.41	0.42	3.10	0.35
Ground floor slab structure type 1	2.97	0.27	0.27	0.35
Ground floor slab structure type 2	2.55	0.29	0.29	0.35
Slab structure type 3	3.22	0.40	2.74	0.30
Flat roof type 1	0.51	0.13	0.13	0.25
Flat roof type 2	0.50	0.13	0.13	0.25
Windows	5.99	1.4	1.4	2.00

From Table 3 it can be concluded that there are large differences between the allowed and existing values, as well as the newly acquired values in the improved scenarios, especially in the facade walls. Facade walls in the current state have very high U coefficients, they are made only of rogh exposed concrete without any external protection layers and they have the largest share in reducing the total transmission losses through the envelope. All types of facade walls show a significant decrease in U values, especially in scenario 1, compared to the current (U value of facade wall type 1 in the current state is 2.33 W/m^{2}K, in scenario 1 - 0.38 W/m^{2}K and in scenario 2 - 1.54 W/m^{2}K). This indicates the fact that the improvement of the overall energy performance of the building greatly depends on the thermal insulation of the envelope, especially the exterior facade walls.

3.4. Financial analysis

Finally, financial analysis of the energy consumption costs for district and electrical heating of the current state and both scenarios are made, graphically shown in Fig. 6. From the analysis it can be concluded that the costs in the current state are higher by 35% comparing to Scenario 1 and by 18% to Scenario 2. Scenario 1 has lower costs by 22% from Scenario 2. The highest costs are observed during winter months, while the smallest during summer, which indicates the great need for heating in winter, but also the fact that the dormitory doesn't work in summer.

These analysis show the important role of the thermal insulation not just in improving the energy efficiency of the building by reducing its energy consumption and transmission losses, but also in reducing the financial costs for building maintenance.

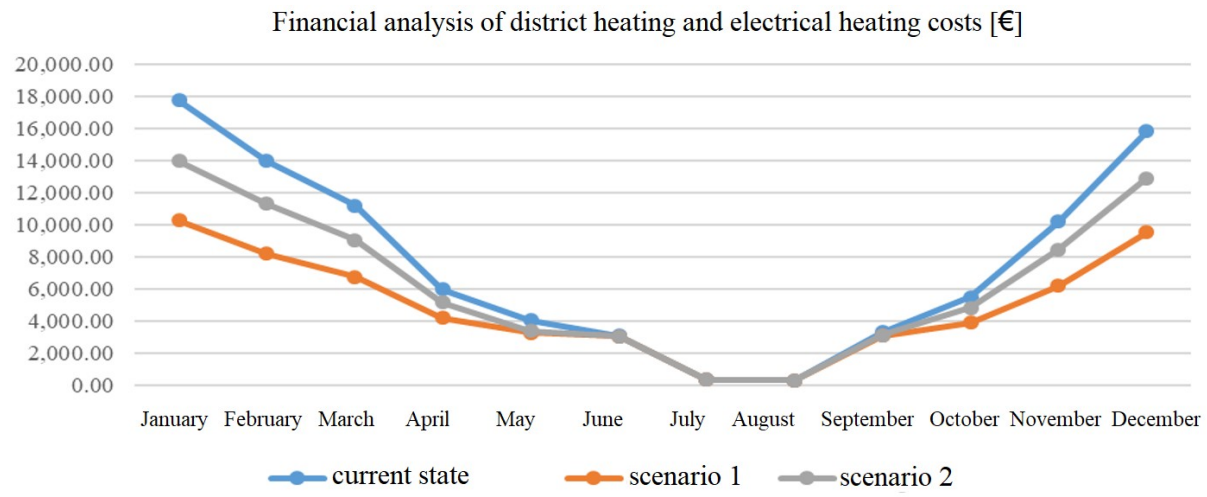


Figure 6 – Comparisons of the cost analysis between the current state and both scenario

4. CONCLUSION

Based on the conducted analyzes, it can be concluded that Modernist architecture in Skopje is an endangered cultural heritage whose energy efficiency, sustainability, emissivity and costs need to be improved. From the investigated nanomaterials, the aerogel plaster (scenario 1) and the nano ceramic coating (scenario 2), are materials that leave a minimal impact regarding the authenticity of the buildings. The dynamic energy simulations for the current situation and the two improved scenarios, showed that in the district heating energy consumption analysis, scenario 1 has lower consumption than the current state by 52%, and scenario 2 by 23%. Electricity consumption for heating in scenario 1 is lower by 65%, and scenario 2 by 51% compared to the current state. Scenario 1 has lower CO_2 emissions by 45%, and Scenario 2 by 20% compared to the current state. Finally, the financial costs of the current state are higher by 35% compared to Scenario 1 and 18% compared to Scenario 2. From the energy simulations it can be concluded that Scenario 1 gave better results in terms of thermal insulation properties and energy efficiency, but Scenario 2 has less impact on the authentic appearance of the selected case study building.

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