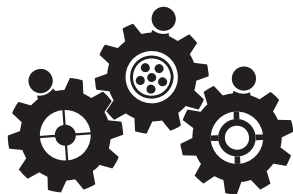




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Faculty of Mechanical Engineering



DEMI 2025

**17th International Conference on
Accomplishments in Mechanical
and Industrial Engineering**

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Banja Luka, 29–30 May 2025

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CONTENT

KEYNOTE LECTURE	1
1. MIRCE SCIENCE: FUNCTIONABILITY ENGINEERING AND MANAGEMENT J. Knezevic	3
2. THE LEAN AND GREEN FUTURE: SIMULATE. OPTIMIZE. TRANSFORM T. Berlec, G. Janjić, Z. Tanasić	15
3. HARNESSING THE EARTH'S HEAT: THE EVOLUTION OF GEOTHERMAL DISTRICT HEATING IN REYKJAVIK V. Hjörleifsdóttir	23
PRODUCTION AND COMPUTER-AIDED TECHNOLOGIES	27
1. CUTTING FORCE AND VIBRATION IN END MILLING PROCESS Sanel Gredelj, Ismet Fatkić	29
2. TEMPERATURE MEASUREMENT DURING THE PROCESS OF WELDING TUBES USING THE TIG METHOD M. Mumović, N. Šibalić	39
3. OPTIMIZATION OF MACHINE LEARNING MODEL FOR PREDICTION OF TOTAL OPERATION TIME IN TURNING OF AISI 304 A. Trajković, M. Madić	45
4. PREDICTION OF SURFACE ROUGHNESS IN TURNING USING ARTIFICIAL NEURAL NETWORKS D. Marinković, L. Mejić, A. Živković, C. Mladenović, M. Knežev, A. Antić	53
5. ANALYSIS OF SPECIFIC CUTTING FORCE IN TURNING OF 42CRMO4 STEEL M. Madić, M. Trifunović, J. Stanojković, D. Rodić, P. Janković	59
6. ANALYSIS OF THE INFLUENCE OF EMULSION ON THE FLEXURAL MECHANICAL PARAMETERS OF FDM 3D-PRINTED PLA AND PLA+CF MATERIALS S. Novšak, A. Nahtigal, L. Tkalčec, K. Simerl, J. Stušek, E. Hozdić	65
7. EFFECT OF INFILL DENSITY ON FLEXURAL PROPERTIES OF FDM 3D PRINTED POLYMER AND COMPOSITE MATERIALS N. Hodnik, M. Markelj, M. Gril, N. Draksler, A. Rogelj, E. Hozdić	77
8. FEM ANALYSIS OF PUNCHING AND BLANKING TOOL S. Randelović, S. Mladenović, M. Trajković-Milenković, A. Zorić, N. Kostić	89
9. RECONFIGURABLE CONTROL SYSTEM FOR MACHINE TOOLS WITH A SWITCHABLE KINEMATIC AND VARIABLE EXECUTION FLOW OF THE KINEMATIC ALGORITHM Z. Dimić, S. Živanović, J. Vidaković, A. Dević	95

10. THE INFLUENCE OF DWELL TIME ON THE COLLECTED DATA DURING LINEAR DISPLACEMENT MEASUREMENTS OF MACHINE TOOLS	101
A. B. Budimir, S. Tabaković, M. Zeljković, S. Živanović, Z. Dimić	
11. LAYOUT SCHEDULING IN FUNCTION OF MATERIAL FLOW VARIANT TYPE	107
M. Gajanin, S. Borojević, D. Kramar, G. Jotić, M. Marković	
12. EXPERIMENTAL ANALYSIS OF NANO-FLUID BASED COOLING AND LUBRICATION INFLUENCE ON CUTTING FORCES IN MILLING	115
B. Sredanovic, G. Globocki Lakic, D. Kozak, G. Simunovic	
13. ENERGY CONSUMPTION MODELLING AND OPTIMIZATION IN HIGH EFFICIENCY MILLING	123
B. Sredanovic, D. Cica, J. Markovic, D. Vujasin, G. Mijuskovic	
14. STRATEGIC PROCESS PLANNING FOR PRISMATIC COMPONENTS: AN OPTIMIZATION APPROACH USING SOLIDCAM	131
D. Božić, M. Milošević, J. Vukman, M. Đurđev, D. Lukić	
ENERGETICS AND THERMAL ENGINEERING	139
1. OCCURRENCE OF FATIGUE ON THE TURBINE AND HYDROMECHANICAL EQUIPMENT	141
Srđan Bulatović, Vujadin Aleksić, Biljana Prochaska, Bojana Zečević	
2. ANALYSIS OF POTENTIAL AND CONCEPTUAL DESIGN OF A WIND FARM	147
V. Vilotijević, A. Dubljević, U. Karadžić	
3. EMISSION OF NITROGEN OXIDES – REGULATION, REDUCTION AND CASE STUDY	155
Luka Marinović, Dejan Mitrović	
4. THE EFFECT OF SLIDING WINDOW TECHNIQUE ON DECISION TREE TIME SERIES FORECASTING IN DISTRICT HEATING SYSTEM	163
Milica Tasic, Ivan Ciric, Vladan Jovanovic, Marko Ignjatovic, Dejan Mitrovic	
5. TECHO-ECONOMIC ANALYSIS AND ENHANCING ENERGY EFFICIENCY IN A RESIDENTIAL BUILDING	171
M. Velemir Radović, D. Nikolić, N. Popović	
6. ENERGY EFFICIENCY ANALYSIS OF PUBLIC PRESCHOOL EDUCATION INSTITUTIONS	179
M. Stanković, M. Mančić, M. Laković-Paunović, M. Rajić	
7. EMHD FLOW AND HEAT TRANSFER OF NANOFLUIDS THROUGH A POROUS MEDIUM WITH THERMAL RADIATION	187
J. D. Petrović, M. Nikodijević Đorđević, M. Kocić, J. Bogdanović Jovanović, Ž. Stamenković	
8. EXAMINATION OF THE HUMIDITY OF WASTE AT THE NIS LANDFILL	195
Ljubica Stojkovic, Dragoslav Pavlovic, Saša Pavlovic, Milan Grozdanovic, Vladan Jovanovic, Gradimir Cvetanovic	

9. ENERGY ANALYSIS OF THE PHOTOVOLTAIC APPLICATION ON THE SOLAR GREENHOUSES – CASE STUDY	199
Danijela Nikolić, Nebojša Jurišević, Saša Jovanović, Zorica Đorđević, Minja Velemir-Radović	
10. ADVANCED SOLAR ENERGY SYSTEMS: CURRENT STATE AND OPTIMIZATION STRATEGIES – A COMPREHENSIVE REVIEW	205
E. Stefanoska, S. Stavreva, I. Andreevski, P. Živković, B. Dimovski, S. Popovska-Vasilevska	
11. GEOTHERMAL WATER CHEMISTRY IN ICELAND AND SERBIA: IMPLICATIONS FOR ENERGY AND ENVIRONMENTAL APPLICATIONS	215
D. C. Finger, D. Đorđević, E. J. Asbjornsson, A. Mihajlidi, S. Sakan	
12. IMPROVEMENT OF RICE QUALITY BY APPLYING PROCESS OF PADDY PARBOILING	223
F. Mojsovski, V. Mijakovski	
13. MULTIDIMENSIONAL FEASIBILITY ASSESSMENT MODELS ARE VITAL FOR THE SUCCESSFUL DEPLOYMENT OF PICO-SCALE HYDROPOWER TECHNOLOGY IN WATER INFRASTRUCTURE	227
Bjarnhedinn Gudlaugsson, Bethany Marguerite Bronkema, Ivana Stepanovic, David C. Finger	
14. ESTIMATING HIGH HEATING VALUE OF SERBIAN COALS USING ULTIMATE ANALYSIS DATA	237
Vladimir V. Jovanović, Mirko S. Komatina, Vasilije Manović	
15. CFD MODELING OF MICROPOLAR FLUID FLOW	243
Miloš Kocić, Živojin Stamenković, Jelena Petrović, Veljko Begović	
16. A DETAILED PARAMETRIC ANALYSIS OF A STIRLING ENGINE COUPLED WITH A SOLAR DISH CONCENTRATOR	253
Dimitrios N. Korres, Christos Sammoutos, Panagiotis Lykas, Saša R. Pavlović, Marko Peric, Evangelos Bellos	
17. DECADE ANALYSIS OF KOPAONIK WIND ENERGY POTENTIALS	263
P. Živković, J. Podunavac, E. Stefanoska, S. Stavreva, G. Cvetanović, C. Barz	
18. ASSESSMENT OF THERMOPHYSICAL PROPERTIES OF NATURAL GAS / HYDROGEN BLENDS FOR INDUSTRIAL APPLICATIONS	269
J. Podunavac, N. Tomić, P. Gruborović, M. Tomić, A. Anđelković, M. Kotur	
19. INFLUENCE OF CROSSWIND INTENSITY ON THE PERFORMANCE OF AIRCOOLED CONDENSER	277
J. Škundrić, I. Mujanić, D. Knežević, S. Laloš, M. Lazarević, D. Đurica	
20. EXPERIMENTAL DETERMINATION OF SMALL FLOW RATES INSIDE HYDRAULIC COMPONENTS	285
D. Knežević, S. Laloš, J. Škundrić, A. Kenjić	

21. HYDROPOWER RESERVOIR INFLOW FORECASTING USING TIME SERIES NEURAL NETWORKS	293
B. Marinović, M. Kašiković, A. Anđelković	
22. THE LCA ANALYSIS OF A SOLAR THERMOELECTRIC COOLING AND HEATING SYSTEM	297
M. B. Pupčević, S. Papuga, M. Kotur, B. Knežević, M. Pokusova, D. Erceg	
23. SIMULATION BASED ASSESSMENT OF UNUTILIZED PERFORMANCE OF AN INSTALLED ROOFTOP PHOTOVOLTAIC SYSTEM	307
M. Mancic, M. Rajic, M. Lakovic, M. Djordjevic, M. Petronijevic, L. Pantic	
24. A PRELIMINARY ASSESSMENT OF ENERGY RETROFITTING FOR SINGLE-FAMILY HOUSES IN MONTENEGRO	313
Esad Tombarević, Milan Šekularac	
25. OPTIMIZATION OF ENERGY CONSUMPTION IN THE PROCESS INDUSTRY BY APPLYING THE CRITICALITY ASSESSMENT ALGORITHM	319
D. Branković, Z. Milovanović	
26. ANALYSIS OF ENERGY EFFICIENCY OF BUILDINGS IN MONTENEGRO USING MEEC SOFTWARE	331
J. Ćirković, M. Šekularac, E. Tombarević	
MECHANICS AND DESIGN	341
1. DIAGNOSIS OF IDLER FAULTS UTILIZING SHORT TIME FOURIER TRANSFORM AND CONVOLUTIONAL NEURAL NETWORKS	343
M. Milovančević, S. Stojičić, M. Miljanović, N. Simonović, D. Trnavac	
2. WORKBENCH FOR VIBRATION TESTING OF ROLLING BEARINGS	355
Radoslav Tomović, Aleksandar Tomović	
3. USAGE OF PLANETARY GEAR TRAINS IN WIND TURBINE POWER TRANSMISSIONS	361
J. Stefanović-Marinović, S. Troha	
4. IMPACT OF A CUSTOMIZED SHAPE FUNCTION ON THE PREDICTION OF VIBRATIONS IN COMPOSITE LAMINATES USING SHEAR DEFORMATION THEORY	367
A. Radaković, D. Čukanović, G. Bogdanović, A. Nešović, P. Knežević, N. Velimirović	
5. HYDRODYNAMIC AND STRUCTURAL ANALYSIS OF AN OSCILLATING UNDERWATER ENERGY HARVESTER IN RIVER FLOW CONDITIONS	375
C. Pareja, D. Finger, J. Rosselló	
6. COMPARATIVE ANALYSIS OF THE ANALYTICAL AND NUMERICAL MODELS FOR DIFFERENT TYPES OF BEAM-TO-COLUMN CONNECTION	381
M. Piskulic, R. Vujanac, A. Perovic, Z. Djordjevic, M. Blagojevic, N. Miloradovic	

7.	COMPARATIVE ANALYSIS OF APPLICATIONS OF DIFFERENT STORAGE SYSTEMS	389
	N. Miloradović, R. Vujanac	
8.	ANALYSIS OF THE STRESS-STRAIN STATE OF A COMPOSITE PRESSURE VESSEL	399
	I. Golubović, Z. Djordjević, S. Kostić, D. Nikolić	
9.	INFLUENCE OF KERR'S ELASTIC FOUNDATION ON FREE VIBRATION OF FUNCTIONALLY GRADED PLATE	405
	G. Bogdanović, D. Čukanović, A. Radaković, P. Knežević	
10.	THE INFLUENCE OF THE MOUNTING WAY AND ORIENTATION OF UNIVERSAL GEARED MOTOR REDUCERS WITH EXTERNAL HELICAL GEARS ON THE LOAD OF FOUNDATION BOLTS	411
	M. Rackov, M. Tica, I. Knežević, S. Kuzmanović	
11.	ANALYSIS OF ACOUSTIC EMISSION GENERATED BY DYNAMIC DISTURBANCES IN THE MECHANICAL SYSTEM	421
	V. Golubović-Bugarski, S. Petković, G. Globočki-Lakić, G. Tošić, G. Jotić	
	MECHATRONICS AND ROBOTICS	429
1.	SPEED CONTROL OF A DC MOTOR BASED ON SYSTEM IDENTIFICATION	431
	D. Erceg, B. Z. Knežević, Z. Grahovac, M. Pupčević, R. Al Afif	
2.	AI-BASED ROBOT VISION ALGORITHM FOR FRUIT RIPENESS CLASSIFICATION	441
	N. Ivačko, D. Stojiljković, D. Jevtić, M. Simonović, I. Ćirić	
3.	MECHATRONIC APPROACH TO THE DESIGN AND ANALYSIS OF A CARTESIAN ROBOT	449
	A. Osmanović, M. Čabaravdić, B. Knežević, J. Halilović, K. Varda, D. Erceg	
4.	HYDRAULIC SYSTEM OF THE ACTIVE ABOVE-KNEE PROSTHESIS	459
	A. Tomovic, M. Damjanovic, R. Tomovic, N. Rasovic	
5.	DEVELOPMENT OF A ROBOTIC EXPERT CHESS-PLAYING SYSTEM BASED ON THE MINIMAX ALGORITHM	465
	S. Savić, D. Erceg, B. Z. Knežević, S. Grujičić	
6.	DESIGN OF REAL-TIME STEPPER CONTROLLER FOR 6DOF ROBOT ARM	475
	A. Dević, J. Vidaković, N. Živković, Z. Dimić	
	AUTOMOTIVE AND TRANSPORTATION ENGINEERING	481
1.	THE INFLUENCE OF THE SPOILER ON THE SPORT CAR AERODYNAMICS AND STABILITY	483
	N. Stojanović, A. Belhocine, Ž. Đurić, I. Grujić	
2.	ANALYTICAL DETERMINATION OF THE INFLUENCE OF EXPLOITATION CONDITIONS OF THE ELECTRIC VEHICLE BATTERY CAPACITY BY THE APPLICATION OF THE TAGUCHI METHOD	489
	I. Grujić, Ž. Đurić, N. Stojanović	

3.	THE INFLUENCE OF THE APPLICATION OF TRIBOLOGICAL INSERTS ON THE TEMPERATURE OF THE FRICTION PAIR (PISTON-CYLINDER) IN AN IC ENGINE	495
	Ž. Đurić, J. Glišović, I. Grujić, N. Stojanović, S. Petković, A. Davinić	
4.	VEHICLE RIDE COMFORT: SUBJECTIVE & OBJECTIVE EVALUATIONS WITH ANN MODEL	505
	S. Mačužić Saveljić, I. Saveljić	
	QUALITY AND ECOLOGY	513
1.	REENGINEERING REAL ESTATE BUSINESS PROCESSES – THE ROLE OF AI IN QUALITY MANAGEMENT	515
	M. Rajić, P. Milosavljević, Z. Stanković, M. Tadić	
2.	STRATEGIC INTEGRATION OF SWOT, PORTER'S FIVE FORCES, AND BLUE OCEAN STRATEGY FOR COMPETITIVE ADVANTAGE: A CASE STUDY ON STARTUPS IN SERBIA	525
	M. Rajić, Z. Stanković, P. Milosavljević, B. Maksimović	
3.	INNOVATING THE BUSINESS MODEL AS A STRATEGY FOR BUSINESS IMPROVEMENT	535
	A. Kitić, M. Radišić, M. Rajić	
4.	A LIFE CYCLE ASSESSMENT OF ENERGY HARVESTERS IN EUROPEAN WATER DISTRIBUTION NETWORKS: A CASE STUDY APPROACH	541
	B. Bronkema, B. Gudlaugsson, X. Escaler, D. Finger	
5.	ENVIRONMENTAL IMPACT ASSESSMENT USING THE PROMETHEE METHOD	549
	M. Dragić, N. Suvajčević	
6.	TPM AS A STRATEGIC TOOL FOR IMPROVING PRODUCTION PERFORMANCE – FLOW CHART	555
	Z. Tanasić, G. Janjić, M. Vuković, T. Berlec, N. Sremčev	
7.	MODELING DECISION TREE IN DISASSEMBLY PLANNING OF END-OF-LIFE PRODUCTS	561
	D. Mlivić, Z. Kunica, N. Tomičić	
8.	MULTICRITERIA ANALYSIS OF GLOBAL WARMING POTENTIAL IMPACT ON THERMAL INSULATION SELECTION: SCENARIOS AND SENSITIVITY ASSESSMENT	567
	Slobodan Peulić, Goran Janjić, Darija Gajić, Saša Čvoro	
9.	APPLICATION OF ENGINEERING METHODS IN THE PRODUCTION PROCESS OF PRECISION MACHINE PARTS	577
	M. Vuković, N. Sremčev, Z. Tanasić, G. Janjić, B. Kosec	
10.	MEASUREMENT ACCURACY ANALYSIS USING A COORDINATE MEASURING MACHINE	583
	G. Jotić, B. Štrbac, M. Ranisavljev, S. Borojević, M. Melichar, M. Hadžistević	

11. ENVIRONMENTAL AND MATERIAL OPTIMIZATION OF COMPRESSED HYDROGEN TRANSPORT FROM ICELAND TO THE UK	591
Diego Augusto Costa, Bjarnhéðinn Guðlaugsson, Tariq Ahmed, Jinoop Arackal Narayanan, David Christian Finger	
12. WASTE-TO-ENERGY METHODS AT THE NIS LANDFILL	597
M. Milošević, Lj. Stojković, A. Boričić, A. Milošević	
MAINTENANCE OF ENGINEERING SYSTEMS AND OCCUPATIONAL SAFETY ENGINEERING	601
1. THE IMPORTANCE OF TECHNICAL IMPROVEMENTS IN THE PREVENTION OF ACCIDENTAL SITUATIONS IN THE PROCESS INDUSTRY	603
D. Branković, Z. Milovanović, B. Vranješ	
2. AN ANALYSIS OF HUMAN HAND-ARM VIBRATIONS ON THE EXAMPLE OF WORKERS' EXPOSURE TO VIBRATIONS IN ONE PRODUCTION COMPANY	609
E. Ridžal, V. Golubović-Bugarski, B. Vranješ, G. Globočki-Lakić, M. Todić	
3. ANALYSIS OF THE CAUSES OF ACCIDENTS ON MEANS OF WORK IN A MINING COMPANY – A CASE STUDY	619
B. Vranješ, D. Branković, Z. Milovanović, M. Todić, M. Vajkić, Lj. Figun	
4. VIBRATIONS AND NOISE AS INDICATORS OF DYNAMIC BEHAVIOUR OF MACHINE SYSTEM	625
Neven Teinović-Čolić, Valentina Golubović-Bugarski, Milan Tica, Vladimir Risojević	
MATERIALS AND WELDING	635
1. ANALYSIS OF THE IMPACT OF FILLER MATERIAL QUALITY ON WELD SEAM PROPERTIES IN THE MAG WELDING PROCESS	637
Dragoslav Dobraš, Milisav Marković, Milan Marjanac	
2. THERMAL PROPERTIES OF CU-AL-NI-MN SHAPE MEMORY ALLOY	641
B. Karpe, B. Kosec, M. Bizjak, I. Ivanić, M. Gojić, A. Nagode	



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Techo-economic analysis and enhancing energy efficiency in a residential building

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Abstract

Enhancing energy efficiency in residential buildings is essential for reducing energy consumption, minimizing environmental impact and improving overall sustainability. A comprehensive techno-economic analysis is critical for evaluating the effectiveness of energy efficiency measures in residential buildings. It helps to balance technical feasibility with economic considerations. This paper analyzes the energy performance of a residential building and explores different strategies to enhance its efficiency. The current energy classification of the building is analyzed, and the study identifies strategies for reducing electricity consumption and operational costs. It evaluates these measures' technical feasibility and potential energy savings, highlighting their effect on long-term energy demand and operational costs. It also outlines specific interventions needed to improve the building's energy rating by one level, concentrating on optimizing overall energy performance and sustainability. This paper presents enhancing energy efficiency using Knauf software. The analysis also considers the techno-economic aspects of the proposed measures, assessing their feasibility and cost-effectiveness to ensure a balanced approach to improving energy efficiency.

Keywords

energy efficiency, techno-economic aspects, residential buildings

1. INTRODUCTION

The primary energy challenges today are supply insecurity and the environmental consequences of excessive consumption. Growing energy demand and the depletion of fossil fuels necessitate increased reliance on renewable sources, while reducing CO₂ emissions remains crucial for environmental protection. The increasing global demand for energy, particularly electricity, is driven by population growth, evolving lifestyles, and rapid technological progress. As energy consumption rises, more efficient and sustainable solutions

become increasingly critical. Consequently, developing energy-efficient and environmentally responsible buildings has gained significant attention recently.

In 2022, households in the EU accounted for 25.8% of final energy consumption and 18.1% of gross inland energy consumption, highlighting their significant role in overall energy demand. Natural gas was the primary energy source for households, making up 30.9% of final energy consumption, followed by electricity at 25.1% and renewables and waste at 22.6%. Oil and petroleum products contributed 10.9%, while derived heat accounted for 8.2%. Despite a shift towards cleaner energy, 2.3% of households still relied on coal products (solid fossil fuels). The largest share of household energy use, 63.5%, was dedicated to space heating, emphasizing the sector's dependence on energy for thermal comfort. Notably, renewable energy sources played an increasingly important role in

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household heating, covering 31.4% of total space heating consumption, reflecting a gradual transition towards more sustainable energy solutions [1].

Serbia's final energy consumption in 2023 amounted to 9,302,605 Ktoe, ranking it 21st among 42 countries [2]. Figure 1 presents the annual energy consumption of households. As shown, in 2023, it amounted to 3,388 Ktoe [2].

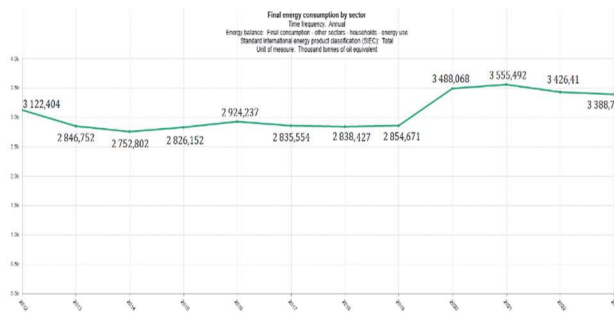


Fig. 1. Annual energy consumption of households in Serbia [2]

The share of end users is shown in the Figure 2.

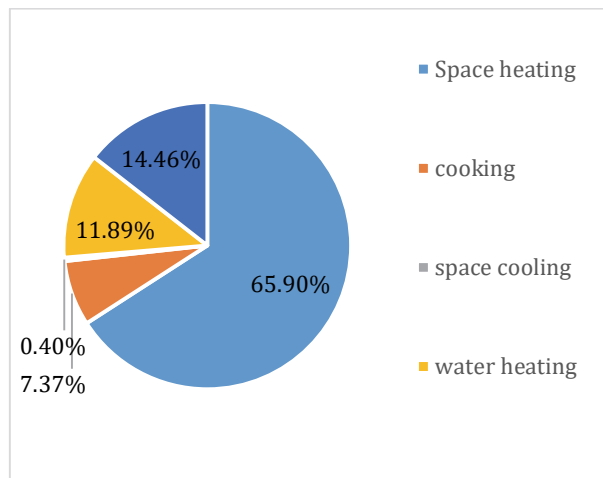


Fig. 2. Final energy consumption in the residential sector by the type of end-use [1]

This study examines a two-story family house, for which annual energy consumption data was collected and its energy efficiency analyzed. Various strategies for improving energy performance were proposed, along with a cost analysis detailing the necessary replacements and investments required to enhance the building's energy efficiency rating by one level. The findings provide a comprehensive assessment of the current state of the house's energy performance and offer practical

recommendations for optimizing efficiency while evaluating the financial implications of such upgrades.

2. ANALYZED OBJECT

A family residence in Kragujevac was selected for the energy consumption analysis, as shown in Figure 3. The house comprises a ground floor and an upper floor with a pitched roof, encompassing a total area of 225 m². Each floor includes a living room, a kitchen with a dining area, a bathroom, and two bedrooms, ensuring a functional and well-organized layout. Furthermore, the property features a basement and a semi-basement, contributing to its overall spatial capacity and utility.



Fig. 3. 3D analyzed object

The structural exterior and load-bearing partition walls are constructed from 25 cm thick brick blocks with mortar. The building's foundation is reinforced concrete designed to mitigate soil temperature fluctuations. Reinforced concrete columns measuring 25x25 cm have been incorporated at the corners and junctions of structural walls. Thermal insulation was installed in 2008 using 5 cm polystyrene boards. The parapet walls are made from the same material as the exterior walls but with a reduced thickness of 20 cm. The interior surfaces are finished with two layers of lime plaster. The residential building features a pitched, double-pitched roof.

The exterior doors and windows, as well as all interior joinery, are standard models manufactured by Jelovica. The windows feature wooden frames, double glazing, thermal insulation, and shutters, and they come in various dimensions. The living areas are finished with oak parquet flooring, while the bathrooms and the kitchens are fitted with ceramic tiles. It is important to note that the building lacks floor thermal insulation.



Fig. 4. The ground floor layout

3. ENERGY CONSUMPTION

Table 1 presents the collected electrical energy consumption data for the entire year of 2024, while Figure 5 presents data for electrical energy consumption spent in lower and higher tariffs. As illustrated in the table, electrical energy consumption peaks in July and reaches its lowest point in February.

Table 1. Electrical energy consumption data for 2024

Month	Sum (kWh)	Amount Due (RSD)
January	148	835.77
February	124	726.46
March	339	1885.6
April	399	2145.22
May	416	2358.15
June	546	2943.42
July	583	3133.58
August	432	2245.41
September	426	2358.14
October	435	2323.98
November	441	2306.9
December	495	2873.96
SUM	4784	26136,59

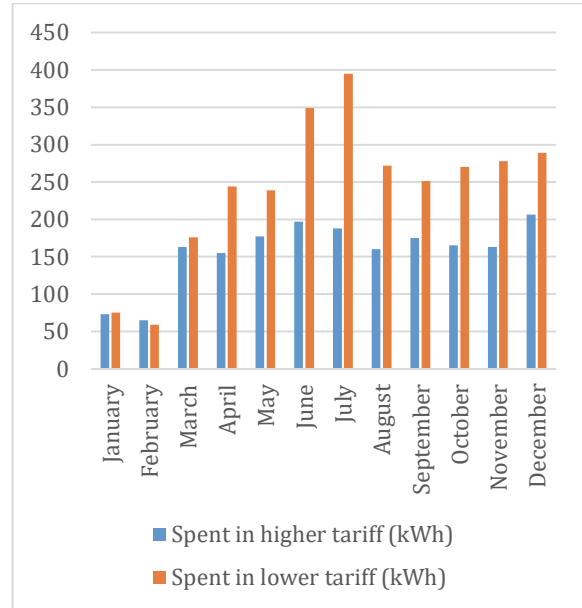


Fig. 5. Electrical energy consumption spent in lower and higher tariffs

Table 2 presents calculations that provide a detailed insight into the electricity consumption and costs per household member, as well as the average price paid per kilowatt-hour.

Table 2. Electrical energy consumption calculations

The specific electricity consumption per user	956.8 [kWh/user]
The specific electricity cost per user	5227.318 [RSD/user]
The average electricity price	5.46 [RSD/kWh]

In the dual-generation residential building, certain daily-use appliances are duplicated; most are well-maintained, with some recently replaced and others relatively old. The building contains a single air conditioning unit located in the upstairs dining room, which achieves the desired temperature during summer after a certain period. Other rooms are ventilated through natural methods, facilitated by opening windows and doors, with the nearby lake contributing to a cooler environment compared to urban areas. During summer, ventilation is performed daily, whereas in winter, it occurs once or twice a week. The lighting system comprises 44 bulbs of various types tailored to room sizes; in some areas, incandescent bulbs have been replaced with compact fluorescent lamps to conserve energy. Lighting is manually controlled via switches without the integration of sensors or automated systems. Figure 6

presents Energy consumption by the type of end users in this household.

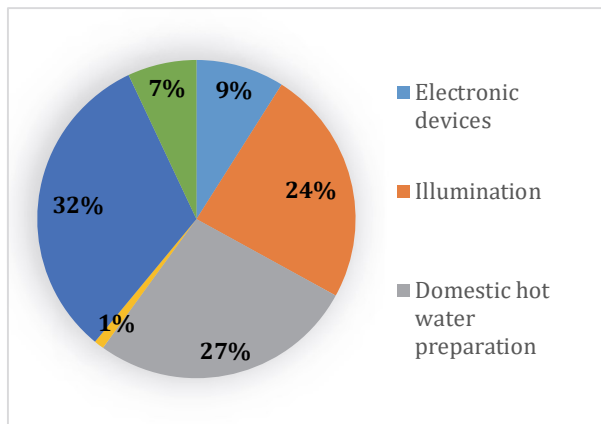


Fig. 6. Energy consumption by the type of end-user

For the preparation of domestic hot water, an instantaneous combination boiler is used for the bathrooms. In the ground floor kitchen, an 8-liter instantaneous water heater is utilized, while a 5-liter instantaneous water heater is employed in the upstairs kitchen. Table 3 presents data on water consumption and the amount due.

Table 3. Water consumption data for 2024

Month	Sum (m ³)	Amount Due (RSD)
January	34	3879.06
February	12	1642.92
March	29	3970.39
April	46	6297.86
May	30	4107.30
June	22	3012.02
July	34	4654.94
August	31	4244.21
September	32	4381.12
October	15	2053.65
November	39	5339.49
December	33	4518.03
SUM	357	37832.74

Calculations for average water price and specific water consumption are presented in Table 4.

Table 4. Water consumption calculations

Average water price	105.97 RSD/m ³
Specific water consumption	71.4 m ³ /user

In the residential building, a natural gas connection was established in 2008. The primary heating source is a Vaillant ecoTEC plus VU 306/5-5 boiler, offering a heating output of 30 kW at an 80/60°C system temperature. This condensing boiler achieves an efficiency of approximately 89.4%, ensuring effective heating. Detailed data on total consumption and costs associated with natural gas supply are presented in table 5.

Table 5. Natural gas consumption for 2024

Month	Sum (kWh)	Amount Due (RSD)
January	5440	27616.24
February	3616	18419.2
March	3192	16280.76
April	1427	7378.99
May	753	3979.67
June	522	2814.61
July	487	2638.1
August	427	2335.49
September	474	2576.06
October	1724	8876.9
November	4465	22701.14
December	4574	23250.88
SUM	27101	138868.04

Considering that natural gas is also used for heating domestic hot water, consumption during summer months can be indicative of winter usage for the same purpose. This is particularly evident from the data in July, August, and September when natural gas was exclusively used for heating domestic hot water. Based on this data, it can be concluded that approximately 5,552 kWh is consumed annually for heating domestic hot water, with the remaining energy used for space heating. Considering the average price of natural gas at 4.57 RSD/kWh, the total annual cost for heating water is approximately 25372.64 RSD. This amount may vary depending on appliance efficiency and current gas prices.

4. BUILDING ENERGY RATING (BER)

For determining the energy efficiency class of the building, the KnaufTerm2S software was used [3]. By inputting actual parameters corresponding to the building's dimensions, location, and construction materials, all

necessary data for establishing the building's energy class were defined. The building's envelope comprises external walls, a roof, a floor-ceiling structure above the unheated space, windows and balcony doors, entrance doors, and the ground floor. The envelope structure diagram is shown in Figure 7.

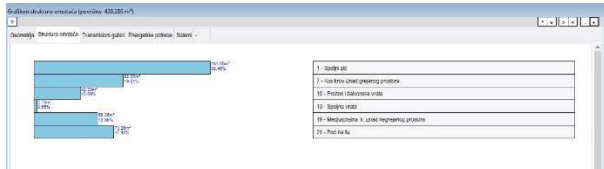


Fig. 7. The envelope structure diagram

The external walls have an area of 161.646 m². They consist of a layer of lime mortar with a thickness of 2 cm, hollow brick blocks laid with a longitudinal mortar of 1 cm thickness, another layer of lime mortar of 2 cm, 5 cm thick polystyrene insulation, and a facade. The block bricks have dimensions of 25 × 19 cm. The heat transfer coefficient is 0.534 W/m²K.

The roof structure consists of concrete and wooden beams, a membrane, and roof tiles. Its surface area is 82 m², and the heat transfer coefficient is 0.675 W/m²K. The total thickness of the roof is 47.5 cm.

The floor-ceiling structure above the unheated space is made of hollow concrete blocks, 20 cm thick, laid in cement mortar 1 cm thick, a 4 cm thick concrete layer, and either parquet or tiles, depending on the area (kitchen or living room). The surface area of rooms with parquet is 47.14 m². The heat transfer coefficient is 1.166 W/m²K. In rooms like the kitchen and pantry, where tiles are installed, the structure consists of concrete blocks, concrete, and ceramic tiles. The surface area of this space is 10.85 m². The heat transfer coefficient is 1.321 W/m²K.

The windows and balcony doors have a total surface area of 42.39 m². These are wooden windows of medium insulation quality. The heat transfer coefficient for the windows is 1.5 W/m²K. The external doors are also made of wood, with a surface area of 2.73 m² and facing west. The heat transfer coefficient for the external doors is 1.6 W/m²K.

Transmission heat losses through the building's envelope are a critical factor in assessing the building's energy efficiency, as they directly

influence the overall energy requirements for heating and cooling. A detailed analysis of these losses facilitates the identification of weak points in the building's thermal insulation and provides a foundation for enhancing energy efficiency through targeted interventions. Figure 8 illustrates these losses, offering a visual representation of how thermal energy dissipates across various parts of the building.



Fig. 8. Transmission heat losses

Based on all the entered parameters, the energy performance certificate of the building has been determined, classifying it in energy class D, as shown in Figure 9.



Fig. 9. Energy classification, grade D

5. ENERGY EFFICIENCY IMPROVEMENTS

Considering that the residential building currently features wooden windows and doors, one potential improvement measure is their replacement with PVC counterparts. This substitution offers numerous advantages, including enhanced durability, superior thermal and acoustic insulation, and minimal maintenance requirements. Additionally, PVC windows and doors are often more cost-effective compared to traditional wooden ones, making them a practical choice for homeowners seeking both quality and affordability.

The proposed improvements include replacing existing wooden windows and doors with PVC alternatives. Specifically, it is recommended to install Eco+ windows from the manufacturer Sunce Marinković. These windows feature a 5-chamber design, a thermal conductivity coefficient of 1.3 W/m²K, low-emission glass

filled with argon, and an installation depth of 70 mm [4]. For the entrance door, the Termo+ model from the same manufacturer is advised, offering excellent thermal and acoustic insulation and a modern design and durability. Implementing these measures will contribute to reducing energy losses and enhancing indoor comfort [5]. Tables 6 and 7 present the specifications of the required windows and door along with their prices, which include manufacturing, transportation, and installation costs [6].

Table 6. The specifications of the required windows

Window dimension (cm)	Quantity	Price (RSD)	Sum (RSD)
180x140	6	40662.3	243973.8
120x140	3	31889.92	95669.76
140x140	4	34522.72	138090.88
60x60	1	9626.93	9626.93
100x90	1	16452.56	16452.56
90x200	2	26936.03	53872.06
SUM			37832.74

Table 7. The specifications of the required door

Door dimension (cm)	Quantity	Price (RSD)	Sum (RSD)
90x210	1	130408.73	130408.73
SUM			130408.73

Intermediate floor structures are insulated primarily to mitigate sound transmission while also contributing to the reduction of thermal losses, representing an additional measure aimed at improving the building's energy performance rating. The project includes the installation of thermal insulation for two types of floor structures: a ground-level floor covering an area of 30 m², and an intermediate floor structure covering 137 m².

For the ground-level floor, thermal insulation is provided in the form of stone wool boards, type Knauf Insulation DF, manufactured in accordance with EN 13162. These boards feature a minimum declared thermal conductivity of $\lambda = 0.037$ W/mK, tolerance class T5, declared compressive strength of 30 kPa at 10% deformation, and a non-combustibility rating of A1. The required thickness of the insulation layer is determined based on the building physics calculations.

For the intermediate floor structure, rigid stone wool boards are to be installed, such as Knauf Insulation POD PLUS, also manufactured in compliance with EN 13162. The boards must have a minimum thickness of 3 cm, a thermal conductivity of $\lambda = 0.039$ W/mK, tolerance class T6, compressibility class CP3, load resistance up to 5 kPa, and a minimum air flow resistance rating of AF5 (MW - EN 13162 - T6 - CP3 - WS - WL(P) - AF5). The specific type of board is selected according to the expected loads and the functional use of the space.

For both floor types, edge strips made of stone wool (e.g., Knauf Insulation), 13 mm thick, are to be installed along the perimeter walls to prevent the transfer of heat and sound to adjacent structural elements. Over the thermal insulation layer, a PE vapor control layer is to be laid, such as Knauf Insulation Homeseal LDS 35, with a vapor diffusion resistance $S_d = 35$ m, thickness of 0.24 mm, and surface mass of 100 g/m², with overlaps at joints of at least 10 cm. If the floor area exceeds 30 m², depending on the type of screed used, the execution of expansion joints is required. This item includes the supply, delivery, and installation of all specified materials, as well as the use of light scaffolding where necessary. Measurement and billing shall be based on the finished floor area in square meters, as presented in tables 8 and 9 [7].

Table 8. The specifications of intermediate floor structures

Material	Price per m ² (RSD)	Total price for 30 m ² (RSD)
Mineral wool Pod Plus 3cm	660	90420
Vapor barrier Homeseal LDS 35	65	8905
Edge strips	40	5480
Cement screed	850	116450
Adhesive/underlay for parquet	150	20550
Standard parquet flooring	1200	164400
Installation of wool + vapor barrier	350	47950
Cement screed application	600	82200
Parquet installation	900	123300
SUM	4815	659655

Table 9. The specifications of ground-level floor

Material	Price per m ² (RSD)	Total price for 30 m ² (RSD)
Mineral wool DF 10cm	1700	51000
Vapor barrier Homeseal LDS 35	65	1950
Edge strips	40	1200
Cement screed	850	25500
Adhesive/underlay for parquet	150	4500
Standard parquet flooring	1200	36000
Installation of wool + vapor barrier	350	10500
Cement screed application	600	18000
Parquet installation	900	27000
SUM	5855	175650

Implementing the recommended energy efficiency measures would elevate the residential building's energy classification from grade D to grade C, as shown in Figure 10. This enhancement signifies a substantial improvement in the building's energy performance, leading to reduced energy consumption and associated costs. Consequently, occupants would benefit from increased thermal comfort and a diminished environmental footprint. Achieving this upgraded energy status aligns with Serbia's broader objectives to enhance energy efficiency in its building sector, addressing the significant potential for energy savings identified in residential structures.

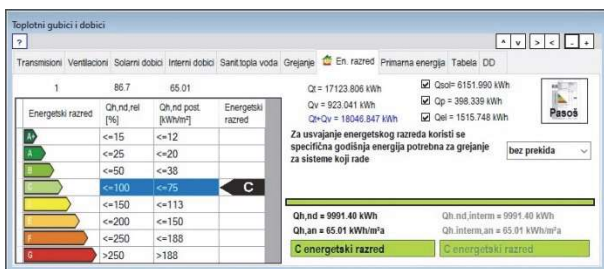


Fig. 10. Energy classification, grade C

According to established energy efficiency benchmarks, window and door replacement may lead to a reduction of approximately 15% in heating costs, whereas floor insulation may contribute an additional 10% savings. Combined, these measures are projected to reduce annual heating expenses by

approximately 28,374 RSD, lowering the total annual energy-related expenditures from 165,004.63 RSD to around 136,630.63 RSD. This corresponds to an estimated return on investment period of about 35 years.

Following the implementation of the recommended measures, transmission losses have been reduced, as depicted in Figure 11.



Fig. 11. Transmission heat losses

Despite the implemented interventions, transmission losses persist through the ground floor, which is situated above the basement. Insulating this floor would yield similar results to previous measures; however, such an investment is not cost-effective, as the basement is solely used for storage.

Implementing energy-saving practices, such as turning off electrical devices when not in use and replacing older appliances with more energy-efficient models, can significantly reduce electricity consumption. Specifically, replacing incandescent light bulbs with LED alternatives offers substantial benefits. LED bulbs consume approximately 80% to 90% less energy than traditional incandescent bulbs and have a significantly longer lifespan [8].

In a scenario where 25 incandescent bulbs are replaced with LED bulbs, the annual energy savings would be approximately 1,048.91 kWh, equating to a financial saving of around 7,619.53 RSD per year. Given that the average price of a single LED bulb is about 270 RSD, the total investment for replacing 25 bulbs would be 6,750 RSD. This investment would pay for itself in less than a year, considering the annual savings. Moreover, LED bulbs emit brighter light, allowing for a reduction in the number of bulbs needed to achieve the desired illumination levels [9].

By adopting these measures, households can achieve a reduction of approximately 78.20% in electricity consumption for lighting, leading to both economic and environmental benefits.

6. CONCLUSION

This study analyzes the potential improvement of energy efficiency in a residential building occupied by a five-member family. The focus is placed on electrical energy consumption, both in total and on a per-user basis. According to the collected data, the household records an annual electricity consumption of 4784 kWh, which corresponds to a specific consumption of 956.8 kWh per user. The associated cost of electricity amounts to 26136.59 RSD annually, or 5227.32 RSD per user. A combination boiler system is employed for both domestic hot water (DHW) preparation and space heating, relying on natural gas as the primary energy source. The total annual expenditure on natural gas reaches 138868.04 RSD, of which approximately 25372.64 RSD is attributed to DHW preparation, while the remaining portion covers heating costs. In summary, the family's total annual expenditure on electricity, water, and heating amounts to approximately 165004.63 RSD, highlighting the significance of targeted energy efficiency measures to reduce both consumption and associated costs.

The residential property's current energy efficiency rating is classified as D, primarily due to factors such as wooden windows and uninsulated flooring. In order to improve the building's overall energy performance and reach a higher energy class, several targeted interventions are proposed. These include the replacement of existing windows and doors with PVC models, an investment amounting to 168241.47 RSD and the insulation of the floor, estimated at 836305 RSD. Together, these measures are projected to yield a cumulative reduction in heating costs of approximately 25%, corresponding to an annual saving of around 28,374 RSD. Following the implementation of these measures, the BER improves to Class C, indicating a significant enhancement in thermal performance and energy conservation. Additionally, efforts to reduce electricity consumption are also considered. In a scenario where 25 incandescent light bulbs are replaced with LED bulbs, the household would achieve an estimated annual energy saving of 1048.91 kWh, translating into a financial saving of approximately 7619.53 RSD per year.

Implementing such sustainable refurbishment practices can significantly improve the building's environmental performance, leading to reduced

energy consumption and increased occupant comfort. By adopting these measures, the household can achieve substantial energy savings, reduce utility costs, and contribute to environmental sustainability.

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