

Revista Română de Inginerie Civilă

Indexată în bazele de date internationale (BDI)

**ProQuest, IET INSPEC, EBSCO, GOOGLE SCHOLAR, CROSSREF,
TDNET, DIMENSIONS, DRJI, J-GATE, INDEX COPERNICUS,
ULRICH'S, JOURNALSEEK, RESEARCH GATE,
SEMANTIC SCHOLAR, ERIHPLUS, WORLDCAT**

Volumul 17 (2026), Numărul 3

The optimal solar capture surface for building heating: method, parameters and scenarios

Suprafața optimă de captare solară pentru încălzirea clădirilor: metodă, parametrii și scenarii 329-347

Mugurel-Florin Tălpigă, Constantin Lazăr, Florin Iordache

Elastoplastic Modelling of the Axial Soil–Pile Interaction

Modelarea elastoplastică a interacțiunii axiale sol–pilot 348-358

Mohamed Lamara, Ahmed Merah, Tayeb Bouziani, Houssam Khelalfa

Contributions to the resolution of issues relating to the performance of fire extinguishing sprinkler systems (2)

Contribuții la rezolvarea unor problematici privind performanța sprinklerelor utilizate în stingerea incendiilor (2) 359-374

Lucian-Vasile Mihoc, Ștefan Dună, Andrei Dună, Cosmina Carmen Florica

Indoor Air Quality and Associated Health Effects. Current Perspectives

Calitatea aerului interior și efectele asupra sănătății. Perspective actuale 375-378

Cristian Păcurar, Adriana Tokar, Marius Adam

The influence of ventilation on CO₂ concentration, compared to the requirements of the I5/2022 regulation

Influența ventilației asupra concentrației de CO₂, raportat la cerințele normativului I5/2022 379-389

Florin-Vladimir Mihailov, GrațIELA-Maria Țârlea

High-porosity cellular glass made by microwave heating with a liquid expanding agent

Sticlă celulară de porozitate ridicată fabricată prin încălzire cu microunde cu un agent de expansiune lichid 390-400

Lucian Paunescu, Sorin Mircea Axinte, Bogdan Valentin Paunescu

Thermal analysis of electrical cables buried in the ground Analiza termică a cablurilor electrice îngropate în sol <i>Sorin Dimitriu, Dragoș Pavel</i>	401-412
TRNSYS - Dynamic Simulation of a Three-Zone House in Iași Heated and Cooled by an Air-Source Heat Pump Simularea dinamică în TRNSYS 18 a unei case cu trei zone din Iași încălzită și răcită cu o pompă de căldură aer-sursă <i>Cătălin Vulpe, Radu Panduru, Marius Alexa, Marina Verdeș, Sebastian-Valeriu Hudîșteanu, Nelu Cristian Cherecheș, Florin Emilian Țurcanu, Claudiu Romila, Cătălin George Popovici, Vasilică Ciocan, Diana-Ana Ancaș</i>	413-422
Night Ventilation as a Key Strategy for Enhancing HVAC Energy Efficiency in Educational Buildings: A Case Study of Energy Savings Ventilarea de noapte ca strategie cheie pentru creșterea eficienței energetice a sistemelor HVAC în clădirile educaționale: Un studiu de caz privind economiile de energie <i>Marius Adam, Adriana Tokar, Alexandru Dorca, Dănuț Tokar</i>	423-428
Decentralized Rainwater Management for Urban Resilience: Principles, Policy Context and a Case Study from Romania Managementul descentralizat al apei meteorice pentru reziliența urbană: principii, context politic și un studiu de caz din România <i>Cristina Iacob, Anagabriela Deac, Dan Mureșan, Teodor Chira</i>	429-436
Energy and thermal performance of radiant heating systems: a comparative study of floor, ceiling and hybrid configurations Performanța energetică și termică a sistemelor de încălzire radiantă: Un studiu comparativ al configurațiilor de pardoseală, tavan și hibride <i>Alexandru Dorca, Adriana Tokar, Marius Adam, Danut Tokar, Daniel Muntean, Calin Sebarchievici, Cristian Pacurar</i>	437-447
The socio-economic impact on a small city through the adoption of energy-efficient outdoor lighting solutions Impactul socio-economic generat de implementarea soluțiilor de iluminat exterior eficiente energetic într-un oraș de mici dimensiuni <i>Anca Manolescu, Stănescu Ionuț</i>	448-461
Engineering Design and Operational Analysis of a Civil Protection Shelter Integrated in Hospital Infrastructure Proiectare inginerescă și analiză operațională a unui adăpost de protecție civilă integrat în infrastructura spitalicească <i>Lucian Mihoc, Mircea Marinescu, Răzvan Zamfira, Andrei Dună</i>	462-467

The role of thermography in the energy assessment of buildings

Rolul termografierii în evaluarea energetică a clădirilor

Adriana Tokar, Marius Adam, Daniel Muntean, Dănuț Tokar, Cristian Păcurar, Alexandru Dorca

468-477

The correlation between biophilic strategies and the energy performance of buildings

Corelația dintre strategiile biofilice și performanța energetică a clădirilor

Alexandra Rusen

478-489

Perspectives and challenges of integrating high-entropy alloys into the HVAC industry through 3D printing

Perspective și provocări ale integrării aliajelor cu entropie ridicată în industria HVAC prin intermediul printării 3D

Gabriel-Victoria Mnerie, Evelin-Anda Laza, Emilia Dobrin, Lavinia-Ileana Sîrbu, Oleksii Gubenia, Ninoslava Tihi

490-505

State of the art of rebars problem in 3D printing of concrete in construction

Stadiul actual al soluțiilor de armare în imprimarea 3D a betonului în construcții

Hicham Bensafi

506-520

Evaluation of the thermal comfort and indoor air quality in a military shelter under summer conditions

Evaluarea confortului termic și a calității aerului interior într-un adapost militar în condiții de vară

Manea-Andrei Damian, Ana-Andreea Vartires, Tiberiu Catalina, Dragos Mihai

521-534

MATRIX ROM
3 Politehnicii Street, Bucharest, Romania
Tel. +4021.4113617, +40733882137
e-mail: office@matrixrom.ro
www.matrixrom.ro

EDITORIAL BOARD

Ph.D. Harish Chandra ARORA, *CSIR-Central Building Research Institute, Roorkee, India*
Ph.D. Assoc. Prof. Arch. Eur. Ing. Lino BIANCO, *University of Malta, Malta*
Ph.D.Prof.Eng. Ioan BOIAN, *Transilvania University of Brasov, Romania*
Ph.D.Assoc.Prof.Eng. Vasilica CIOCAN, *Gh. Asachi Technical University of Iasi, Romania*
Ph.D.Prof. Stefano CORGNATI, *Politecnico di Torino, Italy*
Ph.D.Assoc.Prof.Eng. Andrei DAMIAN, *Technical University of Constructions Bucharest, Romania*
Ph.D.Prof. Yves FAUTRELLE, *Grenoble Institute of Technology, France*
Ph.D.Prof.Eng. Carlos Infante FERREIRA, *Delft University of Technology, The Netherlands*
Ph.D.Prof. Manuel GAMEIRO da SILVA, *University of Coimbra, Portugal*
Ph.D.Prof.Eng. Dragos HERA, *Technical University of Constructions Bucharest, Romania, honorary member*
Ph.D. Jaap HOGELING, *Dutch Building Services Knowledge Centre, The Netherlands*
Ph.D.Lawyer Cristina Vasilica ICOCIU, *Polytechnic University of Bucharest, Romania*
Ph.D.Prof.Eng. Anica ILIE, *Technical University of Constructions Bucharest, Romania*
Ph.D.Prof.Eng. Gheorghe Constantin IONESCU, *Oradea University, Romania*
Ph.D.Prof.Eng. Florin IORDACHE, *Technical University of Constructions Bucharest, Romania - director editorial*
Ph.D.Prof.Eng. Vlad IORDACHE, *Technical University of Constructions Bucharest, Romania*
Ph.D.Prof.Eng. Karel KABELE, *Czech Technical University, Prague, Czech Republic*
Ph.D.Prof. Birol KILKIS, *Baskent University, Ankara, Turkey*
Ph.D.Assoc.Prof.Eng. Catalin LUNGU, *Technical University of Constructions Bucharest, Romania*
Ph.D.habil. Assoc.Prof. Zoltan MAGYAR, *Budapest University of Technology and Economics, Hungary*
Ph.D.Assoc.Prof.Eng. Carmen MARZA, *Technical University of Cluj Napoca, Romania*
Ph.D.Prof.Eng. Ioan MOGA, *Technical University of Cluj Napoca, Romania*
Ph.D.Assoc.Prof.Eng. Gilles NOTTON, *Pascal Paoli University of Corsica, France*
Ph.D.Prof.Eng. Daniela PREDA, *Technical University of Constructions Bucharest, Romania*
Ph.D.Prof.Eng. Adrian RETEZAN, *Polytechnic University of Timisoara, Romania*
Ph.D.Prof. Emeritus Aleksandar SEDMAK, *University of Belgrad, Serbia*
Ph.D. Boukarta SOUFIANE, *Institute of Architecture and Urban Planning, BLIDA1, Algeria*
Ph.D.Assoc.Prof.Eng. Daniel STOICA, *Technical University of Constructions Bucharest, Romania*
Ph.D.Prof. Branislav TODOROVIC, *Belgrad University, Serbia*
Ph.D.Prof. Marija S. TODOROVIC, *Academy of Engineering Sciences of Serbia*
Ph.D.Eng. Ionut-Ovidiu TOMA, *Gh. Asachi Technical University of Iasi, Romania*
Ph.D.Prof.Eng. Ioan TUNS, *Transilvania University of Brasov, Romania*
Ph.D.Assoc.Prof.Eng. Constantin TULEANU, *Technical University of Moldova Chisinau, Republic of Moldova*
Ph.D.Prof.Eng. Ioannis VAYAS, *National Technical University of Athens, Greece*
Ph.D.Assoc.Prof.Eng. Eugen VITAN, *Technical University of Cluj Napoca, Romania*

Romanian Journal of Civil Engineering is founded, published and funded by
publishing house MATRIX ROM
Executive Director: mat. Iancu ILIE

Online edition ISSN 2559-7485

Print edition ISSN 2068-3987; ISSN-L 2068-3987

The optimal solar capture surface for building heating: method, parameters and scenarios

Suprafața optimă de captare solară pentru încălzirea clădirilor: metodă, parametrii și scenarii

Mugurel-Florin Tălpigă¹, Constantin Lazăr¹, Florin Iordache¹

¹Technical University of Civil Engineering Bucharest

Bd. Lacul Tei nr. 122 - 124, cod 020396, Sector 2, Bucharest, Romania

E-mail: talpiga.mugurel@gmail.com, constantin.lazar@phd.utcb.ro, fliord@yahoo.com,

DOI: 10.37789/rjce.2026.17.3.1

Rezumat: Lucrarea analizează dimensionarea instalațiilor solare termice utilizate pentru încălzirea clădirilor și prepararea apei calde de consum, prin introducerea unui parametru esențial de optimizare: raportul dintre capacitatea de transfer termic a clădirii și suprafața de captare solară (H/S_c). Pe baza acestui indicator, este evaluată performanța unui sistem solar instalat într-o clădire colectivă situată în Zona Climatică II (București), utilizând captatoare plane cu $k_c = 3 \text{ W/m}^2\text{K}$ și un regim de temperatură scăzut ($50/30^\circ\text{C}$). Studiul include determinarea parametrilor termici ai buclei solare, analiza randamentelor lunare, calculul gradului de acoperire energetică și evaluarea balanței energetice sezoniere. Rezultatele arată o contribuție solară semnificativă în perioadele de tranziție (martie–aprilie, septembrie–octombrie), cu acoperiri ce depășesc 100%, dar o eficiență redusă în sezonul rece (15–30%). Sunt analizate trei scenarii de dimensionare ($H/S_c = 1.3, 11.3$ și 52.2), evidențiind compromisurile dintre investiție, performanță și riscul de supraproducție. Concluzia principală este că dimensionarea optimă se obține pentru lunile de tranziție (octombrie/aprilie), în timp ce dimensionarea pentru luna critică (decembrie) devine neeconomică fără stocare sezonieră sau surse auxiliare.

Cuvinte cheie: instalații solare termice, performanță energetică, sursă auxiliară

Abstract: This study investigates the sizing of solar thermal systems used for space heating and domestic hot water production by introducing a key optimization parameter: the ratio between the building's thermal loss coefficient and the installed solar collector area (H/S_c). Using this indicator, the performance of a solar thermal installation serving a multi-apartment building located in Climate Zone II (Bucharest) is evaluated. The system employs flat-plate collectors with $k_c = 3 \text{ W/m}^2\text{K}$ and operates under a low-temperature regime ($50/30^\circ\text{C}$). The analysis includes the determination of thermal transfer modules, monthly efficiency assessment, calculation of the solar coverage factor, and evaluation of the seasonal energy balance. Results show high solar contribution during transition months (March–April, September–October), often exceeding 100%, while winter performance remains limited (15–30%). Three sizing scenarios ($H/S_c = 1.3, 11.3$, and 52.2) are compared, highlighting the trade-offs between investment cost, energy yield, and risk of seasonal overproduction. The study concludes that optimal sizing is achieved when the system is dimensioned for transition months (October/April), whereas sizing for the critical

winter month (December) becomes economically inefficient without long-term thermal storage or auxiliary energy sources.

Key-words: solar thermal systems, energy performance, auxiliary source

Introduction

Solar thermal installation evaluation, for building heating for preparing hot water for consumption involves adopting a solar capture surface capable of ensuring an appreciable energy coverage for the consumer served, without the investment in the capture surface being excessively high. To achieve this expressed qualitatively, it is necessary to adopt a parameter built on the basis of both the size of the consumer and another parameter representative of the installed solar surface. Such a parameter can be the ratio between the heat transfer capacity of the heated building, H (W/K) and the installed solar capture surface SC (m²). In this way, the parameter H/SC (W/m²·K) is obtained, representing a kind of thermal “transmittance” of the building envelope in relation to the solar capture surface. Associating the degree of energy coverage offered by the solar installation with the value of the mentioned parameter results in an orientation regarding the value of the solar energy capture surface to be installed.

The size of the consumer is partially reflected by the heat transfer capacity H of the building envelope given that the design heat requirement of the building is $Q_{inc0} = H \cdot (t_{i0} - t_{e0})$. We leave the design temperature difference separately in the idea that an analysis can be made according to the climatic zone in which the building is located. Thus for climatic zone 1 where the design external temperature is $t_{e0} = -12$ °C, we have $t_{i0} - t_{e0} = 32$ °C, for zone 2 we have $t_{i0} - t_{e0} = 35$ °C, etc. Another parameter that influences the degree of energy coverage offered by the solar installation for the building's heat requirement is the sizing of the consumer's heating installation, that is, more precisely, the design temperature couple for the heat agent, i.e. for example $t_{T0}/t_{R0} = 90/70$ °C. However, the more the central heating installation is sized at lower temperature values, for example $t_{T0}/t_{R0} = 80/60$ °C or $t_{T0}/t_{R0} = 60/40$ °C. or even $t_{T0}/t_{R0} = 50/30$ °C, the better the solar installation works, with higher yields and consequently greater contributions to the consumer's energy coverage.

Another important parameter that influences the degree of energy coverage of the solar installation is the quality of the solar collectors expressed by their heat transfer coefficient, K_C . The common range of values for this parameter is 2...3...4 W/m²·K. Thus, good solar collectors are characterized by values of approx. 2 W/m²·K (solar collectors with evacuated tubes), or for average solar collectors values of approx. 3 W/m²·K or for weaker solar collectors values of approx. 4 W/ W/m²·K. However, we must mention that the type of application is important in choosing solar collectors and not in every type of application it is necessary to use very high-performance solar collectors. In this paper, however, we propose to analyze an average case from the point of view of the performance of solar collectors $K_C = 3$ W/m²·K. Regarding the parameter pair t_{T0}/t_{R0} for sizing the surface of the building's central heating installation, the option of low-temperature heating will be chosen, i.e. $t_{T0}/t_{R0} = 50/30$ °C. This requires a

favorable situation for the solar installation but also a larger surface for the central heating installation. Zone 2 characterized by a design external temperature $t_{e0} = -15^\circ\text{C}$ will be considered as the climatic zone.

A collective building of approximately 100 apartments will be considered, characterized by a heat transfer capacity of approximately 14200 W/K.

Methodology adopted

The working procedure involves calculating the thermal transfer modules for the solar collection surface and for the surface of the heat exchanger immersed in the storage tank. Thus for the solar collection surface:

$$E_C = \exp\left(-\frac{F' \cdot k_C \cdot S_C}{1.163 \cdot G_C}\right) = \exp\left(-\frac{F' \cdot k_C}{1.163 \cdot a_C}\right)$$

where:

$$F' = 0.95; k_C = 3 \frac{\text{W}}{\text{m}^2 \cdot \text{K}}; a_C = 50 \frac{\text{L}}{\text{h} \cdot \text{m}^2}$$

$$E_C = \exp\left(-\frac{F' \cdot k_C}{1.163 \cdot a_C}\right) = 0.9522$$
(1)

For the heat exchanger immersed in the storage tank:

$$E_S = \exp\left(-\frac{k_S \cdot S_S}{1.163 \cdot G_C}\right) = \exp\left(-\frac{k_C}{1.163 \cdot a_C} \cdot \frac{S_S}{S_C}\right)$$

where:

$$k_S = 800 \frac{\text{W}}{\text{m}^2 \cdot \text{K}}; \frac{S_S}{S_C} = 0.067$$

$$E_S = \exp\left(-\frac{k_S}{1.163 \cdot a_C} \cdot \frac{S_S}{S_C}\right) = 0.5621$$
(2)

For the thermal transfer module of the solar loop, it results:

$$E_{CS} = \frac{E_C \cdot (1 - E_S) + E_S \cdot (1 - E_C)}{1 - E_C \cdot E_S}$$

where:

$$E_C = 0.9552; E_S = 0.5621$$

$$E_{CS} = 0.9549$$
(3)

Solar loop correction factor:

$$F_R^B = \frac{1.163 \cdot G_C}{k_C \cdot S_C} \cdot (1 - E_{CS}) = \frac{1.163 \cdot a_C}{k_C} \cdot (1 - E_{CS}) = 0.8735$$
(4)

Factorul de corectie al buclei instalatiei de incalzire a consumatorului :

$$F_R^C = 2 \cdot \frac{H}{k_C \cdot S_C} \cdot \frac{t_{i0} - t_{e0}}{t_{T0} - t_{R0}} = \frac{2}{3} \cdot \frac{H}{S_C} \cdot \frac{20 - (-15)}{50 - 30} = 1.167 \cdot \frac{H}{S_C} \quad (5)$$

Correction factor of the installation as a whole:

$$F_R^{BC} = \left(\frac{1}{F_R^B} + \frac{1}{F_R^C} \right)^{-1} \quad (6)$$

Finc factor:

$$F_{INC} = \frac{t_{R0} - t_{e0}}{t_{i0} - t_{e0}} = \frac{30 - (-15)}{20 - (-15)} = 1.286 \quad (7)$$

$$f_u = 0.35 + 0.71836 \cdot \exp \left[-0.1 / \left(\frac{V_a}{75 \cdot S_C} \right) \right] \quad (8)$$

$$\frac{V_a}{S_C} = 75; f_u = 1$$

with $\alpha \cdot \tau = 0.9 \cdot 0.85 = 0.765$

$$\beta_{REF} = \frac{t_{i0} - t_e}{f_s \cdot I} \text{ unde } I = f_{cap} \cdot I_O \quad (9)$$

Efficiency will be :

$$\begin{aligned} \eta_{BC} &= F_R^{BC} \cdot [0.81 - 3 \cdot 1.286 \cdot \beta_{REF}] = \\ &= F_R^{BC} \cdot [0.81 - 3.858 \cdot \beta_{REF}] \end{aligned} \quad (10)$$

knowing :

Incident Thermal Power :

$$P_I = S_C \cdot I \quad (11)$$

And total income in the system:

$$P_{CP} = \eta_{BC} \cdot f_u \cdot P_I = \eta_{BC} \cdot P \quad (12)$$

Having building demand :

$$P_{CONS} = H \cdot (t_{i0} - t_e) \quad (13)$$

Than, solar coverage is :

$$G_{AE} = \frac{P_{CP}}{P_{CONS}} = \frac{\eta_{BC} \cdot f_u \cdot S_C \cdot I}{H \cdot (t_{i0} - t_e)} = \frac{\eta_{BC} \cdot I}{(t_{i0} - t_e)} \cdot \frac{1}{\frac{H}{S_C}} \quad (14)$$

The evaluation of the thermal energy contributions of the solar installation is in this situation dependent on a single parameter, namely the H/S_C ratio. A test of this parameter was carried out in the range $H/SC = 4 \dots 16 \text{ W/m}^2 \cdot \text{K}$. Thus, the H/S_C value was fixed and first the value of the correction factor F_R^C was established, then the correction factor F_R^{BC} . Next, from Mc001-revised, for each month of the year, the intensities of solar radiation on the horizontal plane, IO , were established and based on the orientation factors of the solar collectors, f_{cap} , the effective values of the solar radiation intensity for the inclination angle of 45° and oriented towards the south resulted. Also for each month, the average monthly outdoor temperatures were established and the evaluation of the REF values and the efficiency of the solar collectors η_{BC} was carried out. Based on these, the thermal powers captured by the solar installation P_{CP} and the thermal powers required by the consumer, P_{CONS} , were calculated. The degree of energy coverage of the solar installation, G_{AE} and the related monthly energy were immediately apparent.

Energies :

$$\begin{aligned} E_{BC} &= 0.024 \cdot N_{zile} \cdot P_{BC} (kWh) \\ E_{CONS} &= 0.024 \cdot N_{zile} \cdot P_{CONS} (kWh) \end{aligned} \quad (15)$$

Use case example

1. general and configuration data

The study analyzes the performance of a solar thermal system used for domestic hot water preparation and heating support of a building located in Bucharest.

The solar collectors are installed with an inclination angle of 45° to the horizontal plane and are optimally oriented, with azimuth 0° (south orientation), which ensures efficient capture of solar radiation throughout the year.

The main characteristics of the collector are:

- absorption coefficient: $\alpha = 0.9$
- transparency coefficient: $\tau = 0.85$
- global loss coefficient: $k_C = 3 \text{ W/m}^2 \text{K}$
- geometric factor: $F' = 0.95$ (specific to high-performance collectors)

The heat exchanger in the solar loop has:

- global coefficient: $k_S = 800 \text{ W/m}^2 \text{K}$

The storage tank is sized to:

- according to a specific volume of $50\text{--}80 \text{ l/m}^2$.

The building analyzed has:

- heat transfer capacity: $H = 14200 \text{ W/K}$
- internal design temperature: $t_{i0} = 20^\circ \text{C}$

- external design temperature: $t_{e0} = -15^{\circ}\text{C}$

The temperatures of the heat transfer medium are:

- flow: 50°C
- return: 30°C

2. Evaluation of intermediate parameters

Based on the input data, the characteristic parameters of the system were determined:

- thermal module of the collector: $EC \approx 0.95$
- exchanger module: $ES \approx 0.56$
- solar loop module: $ECS \approx 0.95$

Relevant correction factors:

- solar loop factor: $FRB \approx 0.8735$
- consumer factor: $FRC \approx 13.2$
- overall system factor: $FRBC \approx 0.8193$

Energy utilization factor:

- $f_u = 1$, indicating a correct dimensioning of the storage tank

Unidimensional factor of the installation:

- $F_{INC} \approx 1.28573$.

Mounthly energies analyze

Table 1 the values of energy parameters and external climate characteristics for the studied situation

	Ian	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
I_{oriz}	49.6	85	124.8	167.2	205.6	233.5	200.8	233.2	175.5	114.2	54.2	41.3
t_e	-2.4	-0.2	5	11.2	16.7	20.4	22.4	21.7	17.2	11	5.3	0.3
f_{cap}	1.7609	1.4526	1.2477	1.0518	0.9425	0.8799	0.9027	1.0264	1.2205	1.4546	1.6200	1.6677
I	87.34	123.47	155.71	175.87	193.79	205.45	181.27	239.36	214.20	166.12	87.80	68.87
f_s	4.50	4.00	3.40	3.00	2.70	2.50	2.50	2.70	3.00	3.40	4.00	4.50
β_{REF}	0.0570	0.0409	0.0283	0.0167	0.0063	0.0000	0.0000	0.0000	0.0044	0.0159	0.0419	0.0636
η_{BC}	0.4835	0.5343	0.5741	0.6109	0.6437	0.0000	0.0000	0.0000	0.6498	0.6132	0.5313	0.4627

3.1 Solar radiation and the influence of positioning

The correction factor for tilt and orientation (f_{cap}) varies between:

- **0.88** (summer) and **1.76** (winter)

This indicates that the system is optimized for the cold season, when the energy demand is higher.

The average monthly solar radiation varies between:

- **~68 W/m²** (December) and **~239 W/m²** (August)

3.2 System efficiency

The solar loop efficiency (η_{BC}) has values:

- **$\approx 46\% - 65\%$ in the cold season**
- **0% in the summer** (the system is not used for heating in the summer season)

The maximum efficiency occurs in the months of:

- **May and September ($\sim 64-65\%$)**

3.3 Thermal Power

The power required for heating (P_{CONS}) varies:

- **maximum: ~ 318 kW (January)**
- **minimum: 0 kW (summer)**

The captured power (PCP) reaches:

- **maximum: ~ 174 kW (September)**
- **minimum: ~ 40 kW (December)**

3.4 Energy Coverage Degree

The thermal coverage degree (GAE) highlights the system performance:

- winter:
 - o **January: 16.66%**
 - o **February: 28.86%**
 - o **December: 14.29%**
- spring/autumn:
 - o **March: 52.65%**
 - o **April: 107.87%**
 - o **October: 100%**

- periods of overproduction:

- o May: 333.98%
- o September: 439.24%

This shows that the system produces energy surplus in the intermediate periods.

3.5 Energy

Monthly energy:

- incident energy (EI):
 - o **maximum: ~ 193 MWh (September)**
- energy required (ECONS):

o maximum: ~236 MWh (January)

• energy captured (ECP):

o maximum: ~125 MWh (September)

3.6 Auxiliary consumption

Pump power:

• between ~1000 W and 4300 W

Monthly energy consumption:

• between ~700 kWh and 3100 kWh

This represents approximately 1–3% of the thermal energy produced.

Tabel 2 Bucharest data

	P _{cons}	P _i	P _{cp}	E _I	E _{cons}	E _{cp}	G _{AE}
Jul							
Aug							
Sep	39.76	268.7478	174.6429	193498.4	28627.2	125742.9	439%
Oct	127.8	208.4255	127.8161	155068.5	95083.2	95095.21	100%
Nov	208.74	110.1638	58.53196	79317.92	150292.8	42143.01	28%
Dec	279.74	86.41513	39.98505	64292.86	208126.6	29748.88	14%
Ian	318.08	109.5831	52.98016	81529.83	236651.5	39417.24	17%
Feb	286.84	154.9144	82.77618	104102.5	192756.5	55625.59	29%
Mar	213	195.3632	112.1496	145350.3	158472	83439.27	53%
Apr	124.96	220.6565	134.7975	158872.7	89971.2	97054.23	108%
May	46.86	243.1398	156.5035	180896	34863.84	116438.6	334%
Jun							

4. Conclusions

1. The system is correctly sized, conditioned by generating the entire heating energy needed for the month of October with an optimal utilization factor ($f_u = 1$).

2. The performance is very good in transition periods, where the system can fully cover or even exceed the need.

3. In the cold season, the contribution is significant (15–30%), reducing conventional energy consumption.

4. There is a significant energy surplus in spring and autumn, which suggests:

o the possibility of using it for domestic hot water

o or integration into a hybrid system

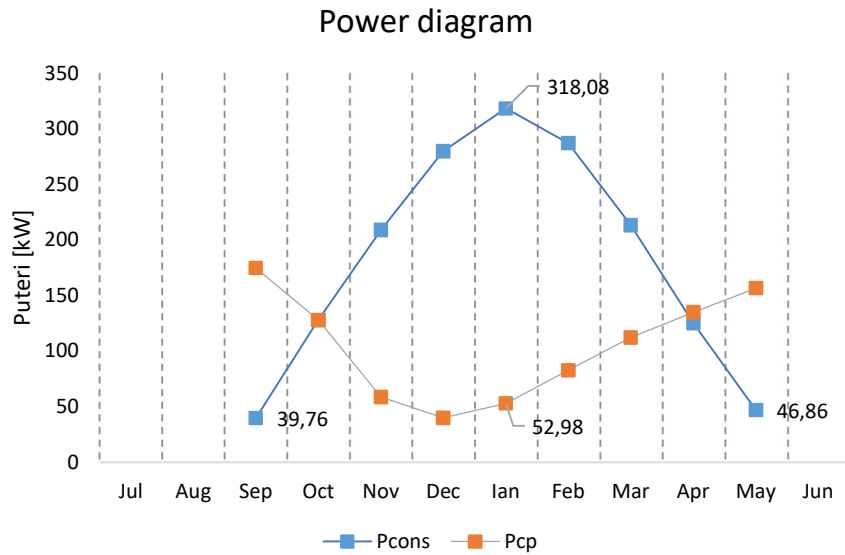


Figure 1 Demand and delivered power

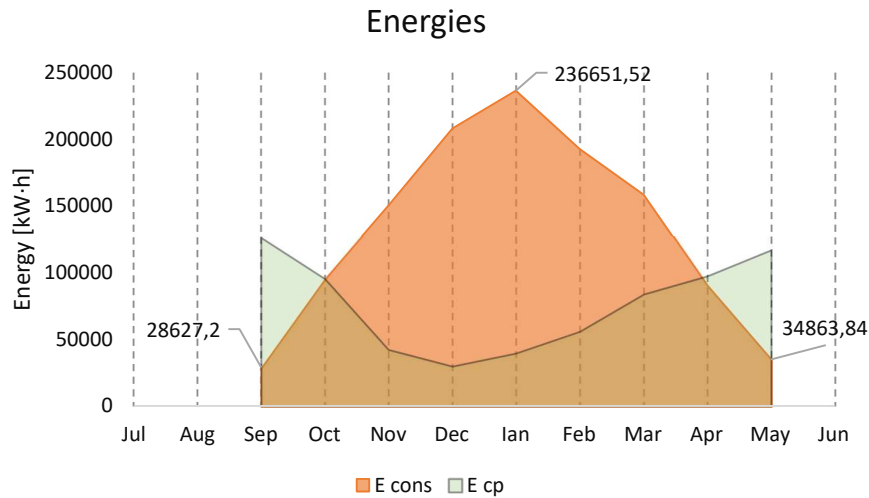


Figure 2 Energies

Seasonal Energy Balance Analysis

Figure 2 illustrates the monthly variation of energy consumption (ECONS) in relation to energy produced or captured (ECP), highlighting the seasonal dynamics of the analyzed system.

1. Consumption Profile (ECONS): A direct correlation is observed between energy demand and the cold period of the year. Consumption records a pronounced upward trend starting with October, reaching a peak load in January (236.65 MWh). This distribution suggests a major dependence on the heating requirement, which is

intensified in winter. Subsequently, demand progressively decreases towards May (34.864 MWh).

2. Correlation with Energy Produced (ECP): The available energy curve shows an inversely proportional behavior to that of consumption. An energy surplus is observed in the transition periods (September and May), while in the winter months (November–February) a significant energy deficit appears. The intersection points of the two curves (approximately in October and April) mark the equilibrium moments of the system, where the demand is satisfied by the solar energy capture system.

Technical Observations:

1. Seasonal discrepancy: The high amplitude of the ECONS curve in relation to the ECP indicates the need for an auxiliary energy source or a long-term storage system to cover the deficit in the period December–February.

2. System efficiency: The minimum consumption values are identified in September (28.63 MWh), reflecting the base load of the system in the absence of seasonal thermal demand.

Local conclusion: Analysis of the diagrams reveals a substantial gap between the availability of the resource and the user's demand, highlighting the challenges related to the energy self-sufficiency of the studied objective in the winter months. It should be noted that the reduction in the energy captured in the period November–January is consistent with the reduction in the incident solar radiation flux.

Aspects regarding the possible sizing of the monthly capture surface.

Figure 3 shows the variation of the capture surface required to fully ensure the energy requirement, depending on the “target month”/“pursued scenario”, highlighting an inverse correlation between the local solar potential and the thermal demand.

Identification of the Critical Month (Maximum Point):

In the climatic context of Bucharest, the month of December represents the critical moment of the system, requiring a maximum surface of 14,560.15 m². This extreme value is the result of the superposition of two unfavorable factors: the lowest incident radiant flux (short days, high cloudiness) and the highest heating requirement (minimum outdoor temperatures).

Seasonality and Curve Dynamics:

1. Winter Period (December – February): High values (>11,000 m²) indicate a low efficiency of solar conversion relative to the thermal load. The reduction in area from December to January suggested by the graph (from 14,560 to 11,271 m²) can be attributed, in zone II, to a possible increase in sunshine in January compared to December, although temperatures remain low.

2. Transition and Summer Period: The steep decrease towards May and the minimum value in September (271.82 m^2) reflect the transition to a regime in which solar radiation is abundant and the energy requirement is probably limited only to the preparation of domestic hot water (DHW).

3. Implications for Design (Optimal Sizing): This inverse assessment demonstrates that a sizing based on the critical month (December) would lead to massive overproportionality in the rest of the year. The ratio between the area required in December and that in September is approximately 53:1, which highlights the need to adopt a compromise solution (e.g. sizing for March or October) supplemented by an auxiliary energy source.

Technical Conclusion: For climate zone II, the graph confirms that the use of solar energy as a sole source for the full coverage of residential/industrial consumption is technically feasible, but economically inefficient without an inter-seasonal storage system or an additional source, due to the order of magnitude variation in the required capture surface.

Analysis of the Dynamics of the H/SC Ratio as an Optimization Indicator

Figure 4 illustrates the monthly evolution of the critical ratio, a parameter that defines the energy self-sustaining capacity of the solar system for the analyzed location (Bucharest, Zone II).

Interpretation of the Maximum Value (September):

The maximum point recorded in September ($52.24 \text{ W/m}^2 \cdot \text{K}$) indicates the period of maximum efficiency of the building-solar system coupling. A high value of the ratio suggests that a minimum capture area is required to compensate for the building's thermal losses, due to the abundant solar radiation and the reduced indoor-outdoor thermal gradient, in other words, the higher the required/production ratio, the greater the need.

Conclusion on the consumer/producer ratio:

The variation of the H/SC ratio demonstrates that, for climate zone II, optimization should not only aim at maximizing the SC surface, but especially at reducing the H value (through energy efficiency measures). A building with a low H will shift the entire curve towards higher values, making the solar system viable for a longer period of the heating season, for the same solar capture surface.

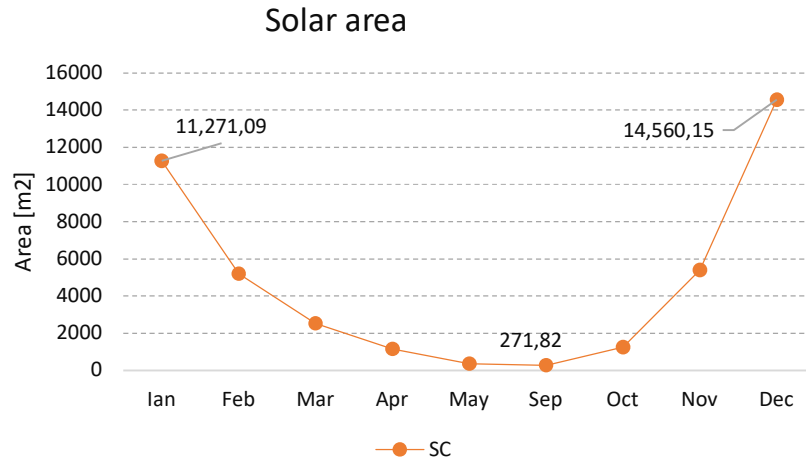


Figure 3 The capture area required to generate the entire consumption required for each month

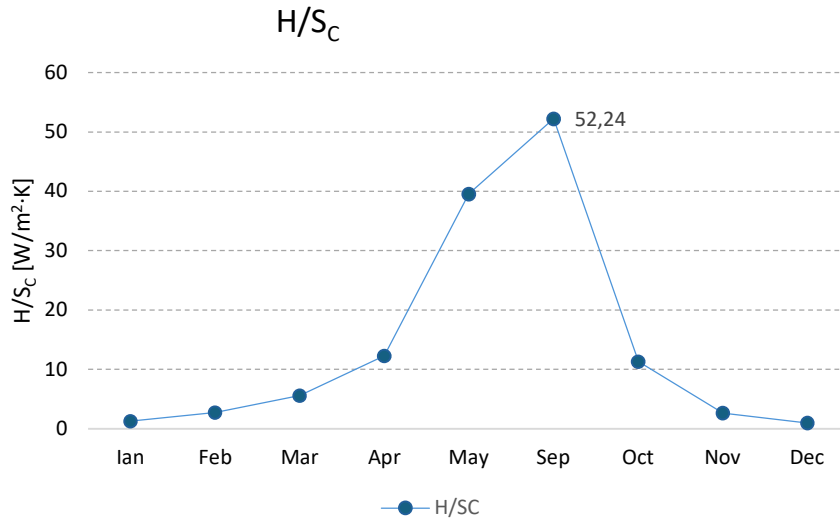


Figure 4 H/SC ratio for generating the entire required consumption for each month

Possible sizing scenarios and comparative analysis

The following are 3 possible scenarios to understand the dynamics of the capture system in the context of an installed consumer characterized by a global transfer coefficient with the exterior $H=14200\text{W/K}$. These graphs illustrate the balance between the captured energy (solar supply) and the required energy (heating demand) over a year, analyzing the impact of sizing the capture surface (SC) compared to the thermal losses of the building (H).

1. Analysis of the $H/S_c=1.3$ Ratio (Oversized System)

• **Figure 5** (Powers) and **Figure 6** (Energies): In this case, the capture surface is very large in relation to the building losses.

- **Comment:** It is observed that the captured power (P_{CP}) exceeds the heating demand (P_{CONS}) almost throughout the year, except for the peak winter period (December-January).

- **Conclusion:** Although the system covers a high solar fraction, it generates a massive energy surplus during the transition and summer periods (the red area visibly exceeds the blue area in Fig. 6). This indicates low economic efficiency and risks of overheating of the installation.

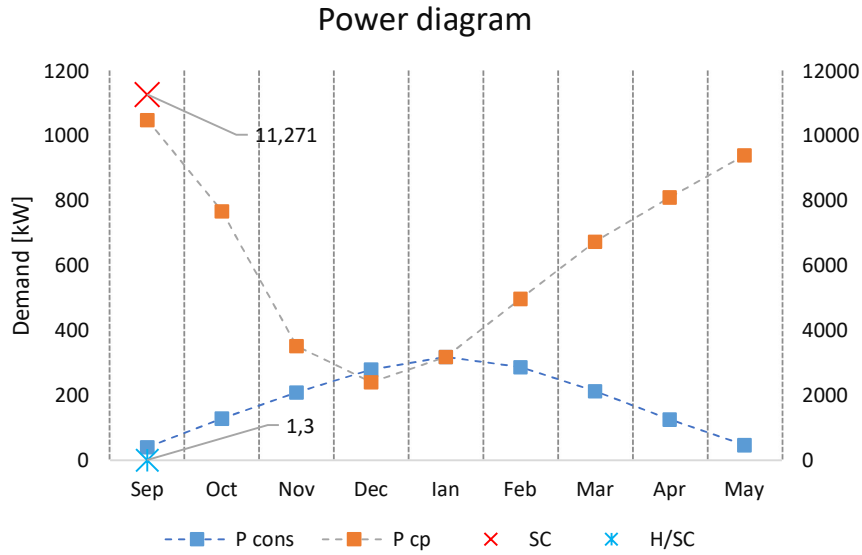


Figure 5 Demand and delivered powers for H/S_c 1.3

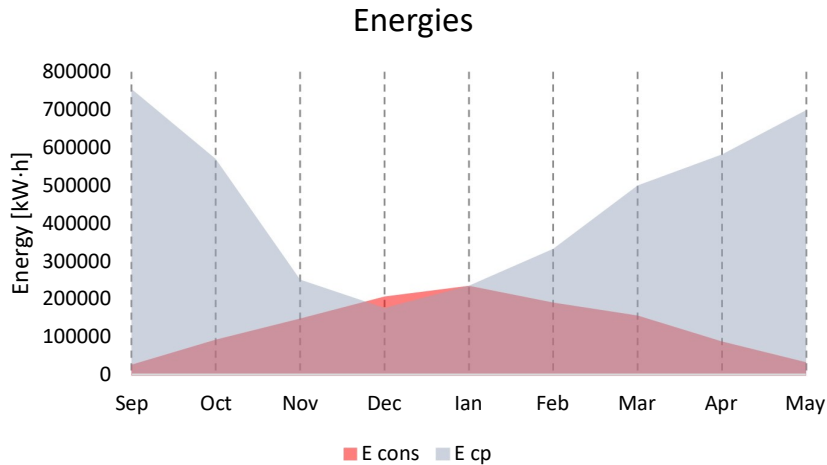


Figure 6 Demand and delivered energies H/S_c 1.3

2. Analysis of the Ratio H/SC = 11.3 (Optimized/Balanced System)

- Figure 7 and Figure 8: This configuration represents a compromise between investment and performance.

- **Comment:** The captured power curve intersects with the required one in the spring and autumn months (**March and October**). During the winter period, the energy deficit is obvious, but the solar contribution remains significant.

- **Conclusion:** This seems to be **the optimal sizing area**. The capture surface is used efficiently, the energy surplus (**red area over blue** in Fig. 8) being much reduced compared to the previous case, which **minimizes losses** and installation costs.

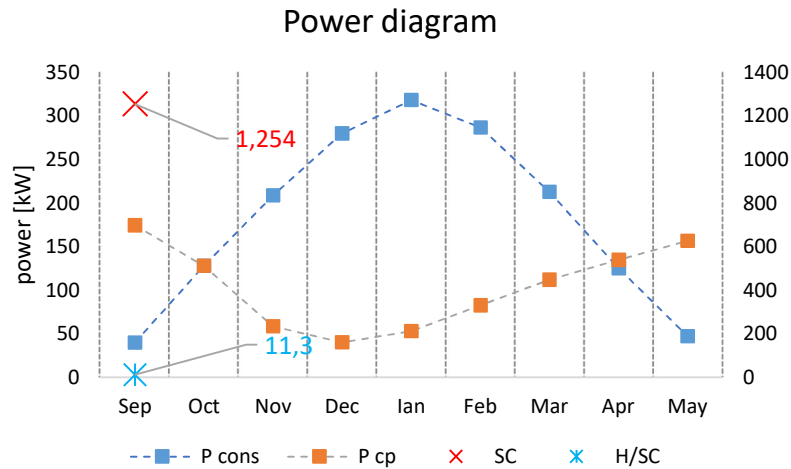


Figure 7 Demanded and delivered power for H/S_c 11.3

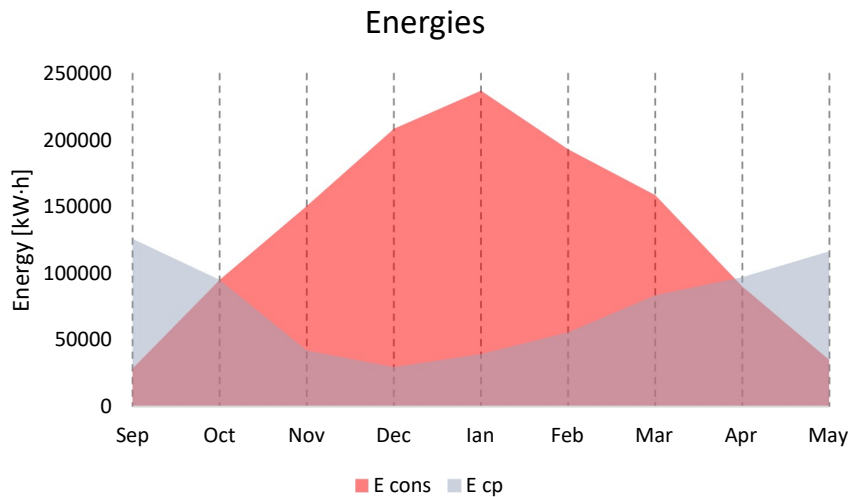


Figure 8 Demanded and delivered energies for H/S_c 11.3

3. Analysis of the Ratio $H/SC=52.2$ (Undersized System)

- **Figure 9 and Figure 10:** Here, the capture surface is too small to support the thermal load.

- **Comment:** The power supplied by the collectors (P_{CP}) is lower than the required (P_{CONS}) even during periods of favorable solar radiation. The solar fraction is minimal.

• **Conclusion:** The system is **undersized**. Although there are no risks of stagnation or overheating (the surplus is almost zero), the solar system has an insignificant impact on the reduction of conventional fuel consumption, not justifying the investment in an active capture system.

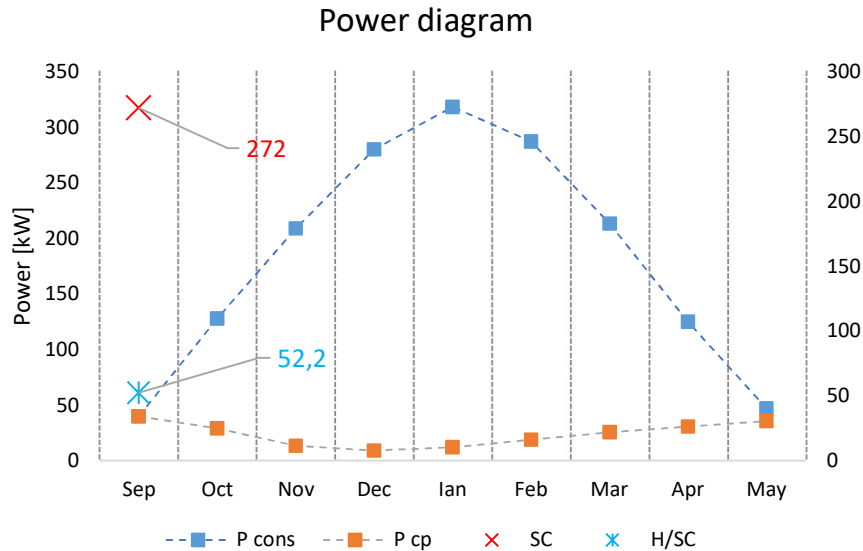


Figure 9 Demanded and delivered Powers for H/S_c 52.2

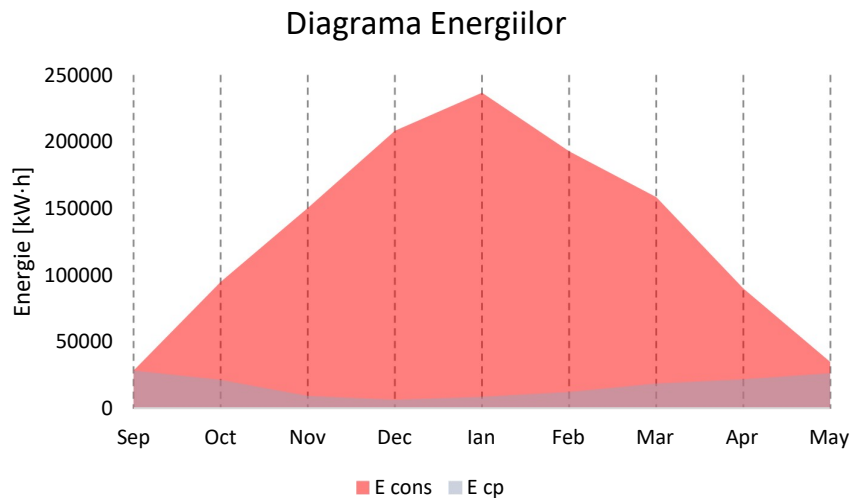


Figure 10 Demanded and delivered energies for H/S_c 52.2

The 3 scenarios were developed to cover the energy needs in Bucharest (Zone II) for a consumer of thermal energy for heating. The summary of the chapter, making a structural parallel between the three situations, is presented in Table 3.

Tabel 3 Strategies and sizing overview

Month	Rapport H/S_C	System behavior
September	Maxim (52.3)	Undersized System: The surface area is very small. It covers consumption only in the warm months, being practically irrelevant for the rest of the heating season.
January	Unfavorable (1.3)	Unfavorable System: The area increases significantly, becoming uneconomical due to the area of 11071m² . Full coverage is obtained in January and visible support in the transition months, but the surplus in the other months is unfeasible.
October	Optimal (11.3)	Optimal System: Similar to April but calibrated for the beginning of the cold season. In the Figures for October, the equality $E_{CP} = E_{CONS}$ is observed at a higher energy level than in September.

Discussions

1. **Energy Capture Translation (ECP):** As we choose a month with a lower **H/ S_C ratio** (from **September** to **October**), the energy capture (**ECP**) bars increase in height throughout the graph. This indicates that an area calculated for a colder month "captures" more energy throughout the rest of the year.

2. **Winter Months Problem (Dec-Jan):** Even in the **October scenario**, the deficit remains huge. Although **S_C is higher**, the **orange bar (E_{CONS})** in January exceeds the **production capacity (E_{CP})** by more than 5 times, confirming that in **Zone II**, solar cannot be the sole source without massive seasonal storage or other auxiliary/backup source.

3. **Surplus Occurrence:** In the **January scenario**, we observe a new phenomenon: in the other months, the **energy captured (E_{CP})** considerably exceeds the need (**E_{CONS}**). This energy surplus must be managed (through thermal discharge or storage or temporary shutdowns of the installation) to avoid system overheating, thus avoiding.

General conclusion:

The overview demonstrates that sizing for **October/April** represents the technical threshold from which the solar system begins to have a real impact on primary energy savings, while sizing for September remains only a symbolic solution, limited to the preparation of domestic hot water.

Symbols

φ_I	the angle of inclination of the solar collectors to the horizontal plane, °;
φ_A	the azimuth angle – the angle between the cardinal orientation of the solar collector to the south orientation, °;
α	the absorption coefficient of the collector plate, -;
τ	the transparency coefficient of the collector's glazed element, -;
S_C	the total surface area of the solar collectors used by the system, m ² ;
k_C	the global heat transfer coefficient of the solar collectors, W/m ² ·K;
F'	the geometric correction factor of the solar collector's performance, -;

S_S	the surface area of the heat exchanger within the solar loop, m ² ;
k_S	the global heat transfer coefficient of the heat exchanger of the solar loop, W/m ² .K;
G_C	the flow rate of the heat agent circulated in the solar loop, l/h;
V_a	the volume of the storage tank, l;
G_{CONS}	the average daily hourly flow rate of hot water consumption, l/h;
S_{INC}	the surface area of the consumer's central heating installation, m ² ;
G_{INC}	flow rate of the heat agent circulated in the heating system, l/h;
t_r	cold water temperature, oC;
t_c	hot water temperature for consumption oC;
t_{T0}	nominal temperature of the heat agent at the entrance to the consumer's central heating system, oC;
t_{R0}	nominal temperature of the heat agent at the exit from the consumer's central heating system, oC;
t_{i0}	standard indoor temperature, oC;
t_{m0}	average nominal temperatures of the heat agent in the consumer's heating system, oC;
t_T	temperature of the heat agent at the entrance to the consumer's central heating system, oC;
t_R	temperature of the heat agent at the exit from the consumer's central heating system, oC;
t_m	average temperatures of the heat agent in the consumer's heating system, oC;
t_{e0}	nominal outdoor temperature, oC;
t_e	outdoor temperature, oC;
t_{em}	average monthly outdoor temperatures, oC;
I	global intensity of solar radiation on the plane of the collection surface, W/m ² ;
I_O	global intensity of solar radiation for a horizontal plane W/m ² , W/m ² ;
a_c	specific flow rate of heat agent in the solar loop, l/h m ² ;
F_C	characteristic factor of inputs-losses of the solar collector, K m ² /W;
F_R^B	correction factor of the heat flux captured by the solar loop, -;
F_R^C	correction factor of the heat flux captured due to the consumer, -;
f_{cap}	correction factor of the global intensity of solar radiation due to the inclination angle of the solar collectors and the angle of deviation from the SOUTH orientation of the solar collectors, -;
F_R^{BC}	correction factor of the heat flux captured by the system composed of the solar loop and the consumer, -;

β_{REF}	synthetic thermal parameter to which the assembly composed of the solar loop of collection and the consumer is subjected, K m ² /W;
η_{BC}	efficiency of the solar collection loop, -;
f_U	utilization factor of the captured energy, -;
G_{AET}	thermal energy coverage degree of the solar loop, %;
G_{AE}	solar loop energy coverage degree, %;
RND	system capture efficiency, %;
P_{CP}	thermal power captured and delivered to the consumer, W;
P_{CONS}	thermal power requested by the consumer, W;
E_I	solar energy incident on the capture surface, kWh;
E_{CP}	thermal energy captured by the solar loop, kWh;
E_{CONS}	energy requested by the consumer, kWh;
Φ_{NEC0}	calculated heat demand of the consumer's building, W;
Nzl	number of days in the month, day/month;
P_P	solar loop pump power, W;
P_{EL}	average daily solar loop pump power, W;
R_{INC}	thermal resistance of the consumer's heating installation, K m ² /W; is the inverse of the global heat transfer coefficient related to the surface of the consumer's heating installation;
F_{INC}	dimensionless correction factor;
H	building heat transfer capacity, W/K.
H/Sc	the ratio between the transfer capacity and the surface area of the solar collectors H/Sc
City	the city for which the calculation is made
I_{up}	Index of the positioning angle relative to the Horizontal and Azimuth

Bibliography:

- [1] – Florin Iordache – Aspecte termo-energetice in domeniul cladirilor si sistemelor de alimentare cu caldura al acestora (culegere de articole) – (Reglarea puterii termice livrate de instalatiile interioare de incalzire centrala, factor important in economia consumului de energie – Florin Iordache, Vlad Iordache – pag. 67-74) – editura Matrix Rom, Bucuresti, 2015;
- [2] – Florin Iordache – Echipamente si sisteme termice. Metode de evaluare energetica si functionala (culegere de articole) – (Sistem sursa cu captatoare solare si pompa de caldura – Florin Iordache, Mugurel Talpiga - pag. 99-113) – editura Matrix Rom, Bucuresti, 2017;
- [3] - Florin Iordache – Echipamente si sisteme termice. Metode de evaluare energetica si functionala (culegere de articole) – (Instalatii de incalzire centrala. Reglajul termic calitativ centralizat – Florin Iordache - pag. 19-28) –editura Matrix Rom, Bucuresti, 2017;
- [4] SR-4839 / 1997 – Instalatii de încălzire. Numărul anual de grade-zile;
- [5] NP-048 / 2000 – Normativ pentru expertizarea termică și energetică a clădirilor existente și instalațiilor de încălzire și prepararea apei calde de consum aferente acestora – Buletinul constructiilor, vol4/2001; 117 Reglarea puterii termice livrate de instalatiile interioare de încălzire centrală, factor important în economia consumului de energie

- [6] Mc001/2006 – Metodologia de auditare energetică a clădirilor noi și existente;
- [7] Comportamentul dinamic al echipamentelor și sistemelor termice, ed. 3-a – Florin Iordache – ed. Matrix Rom – 2008;
- [8] Termotehnica construcțiilor, ed. 3-a – Florin Iordache – ed. Matrix Rom – 2010;

Elastoplastic Modelling of the Axial Soil–Pile Interaction

Modelarea elastoplastică a interacțiunii axiale sol–pilot

Mohamed Lamara¹, Ahmed Merah², Tayeb Bouziani³, Houssam Khelalfa^{1,4}

¹ LGCE, University of Jijel, Jijel, Algeria
E-mail: khelalfahoussam@gmail.com

² Faculty of Civil Engineering and Architecture, Research Laboratory of Civil Engineering (LRGC), University Ammar Telidji of Laghouat, Laghouat, Algeria
E-mail: a.merrah@lagh-univ.dz

³ Structures Rehabilitation and Materials Laboratory (SREML), Department of Civil Engineering, University Amar Telidji of Laghouat, Algeria
E-mail: t.bouziani@lagh-univ.dz

⁴ Faculty of Engineering and Technology, Selinus University of Science and Literature (SUSL), Ragusa, Italy
E-mail: khelalfahoussam@gmail.com

DOI: 10.37789/rjce.2026.17.3.2

Abstract

The development of numerical analysis and the significant progress made in the field of computing have made it possible to consider the increasingly complex behaviour of geo-materials. Using the finite element method and an elastoplastic approach, a model of the behaviour of an axially loaded soil–pile system is proposed. The effect of soil–structure interaction is incorporated through interface elements. The soil is represented by a Mohr–Coulomb model with perfect plasticity. For the numerical analysis of soil–pile behaviour, a nonlinear finite element computation code has been developed. Ultimate loads are determined for a pile subjected to axial compression and tension. The results obtained highlight the importance of the contact zone on the distribution of stresses within the soil.

Keywords: *Geo-materials, soil–structure interaction, elastoplastic behaviour, piles, interface elements, ultimate loads.*

1- INTRODUCTION

The behaviour of geo-materials is often modelled within the framework of linear elasticity. However, experimental results have shown that stress–strain relationships are nonlinear and that part of the deformations is irreversible. It is therefore more appropriate to consider the nonlinear (elastoplastic) nature of these materials when

modelling their behaviour. The advancement of numerical calculation models has made it possible to account for the increasingly complex behaviour of geo-materials. In this field of research, the finite element method (Zienkiewicz, 1973) can be considered an effective and practical tool for simulating the behaviour of foundation soils. One of the main advantages of this method is its ability to handle various issues such as variations in soil properties, complex boundary conditions, and different loading cases.

The modelling of contact problems is a matter of great importance in soil and rock mechanics, whether dealing with contact between two different soil layers, fractures in rock masses, or soil–structure interaction. In such cases, it is not acceptable to neglect the effect of relative movements at the contact zones on the overall behaviour of the structure. For a more accurate numerical analysis of these problems, interface elements have been proposed by various researchers to model soil–structure interaction while considering the relative displacements at the interfaces.

The prediction of the nonlinear response of deep foundations under vertical loads is an important problem in soil–structure interaction. A realistic approach to the analysis of deep foundations must take into account the post-elastic behaviour of the soil. The main objective of this work is to model, using the finite element method, deep foundations subjected to axial loading. The behaviour of the soil–pile system is governed by a Mohr-Coulomb type law. The contact zones are represented by thin layer interface elements. The nonlinear system of equations is solved using an incremental-iterative method with a tangent stiffness matrix to improve convergence. Based on the formulation of the various elements (finite elements and interface elements), a computational code named ANAPLAST, written in Fortran, has been developed in this study.

2- ELASTOPLASTIC BEHAVIOUR OF GEO-MATERIALS.

A material is said to exhibit elastoplastic behavior when, beyond a certain loading level (the yield threshold), it undergoes irreversible (plastic) deformations in addition to reversible (elastic) deformations. More generally, and for three-dimensional cases, the yield threshold is replaced by a surface in stress space, described by a function known as the yield function or plasticity criterion, such that:

$$\text{if } \left. \begin{array}{l} F(\sigma) < 0, \text{ the material behaviour is within the elastic domain.} \\ F(\sigma) > 0, \text{ the material behaviour is within the plastic domain.} \end{array} \right\}$$

2-1- Steps for Formulating an Elasto-plastic Constitutive Law

The formulation of an elastoplastic constitutive law is based on plasticity theory, incorporating an associated flow rule and isotropic hardening. The total strain rate $d\epsilon$ is decomposed into an elastic part and a plastic part:

$$d\epsilon = d\epsilon^e + d\epsilon^p$$

Where $\mathbf{d}\boldsymbol{\varepsilon}$, $\mathbf{d}\boldsymbol{\varepsilon}^e$ and $\mathbf{d}\boldsymbol{\varepsilon}^p$ are the total, elastic, and plastic strain rates, respectively.

Plastic deformation occurs when the stress state reaches the yield surface $\mathbf{F}(\boldsymbol{\sigma}) = 0$. The direction of this plastic strain increment is defined by the plastic potential function $\mathbf{g}(\boldsymbol{\sigma})$. The normal to this surface is determined by the flow rule.

$$(\mathbf{d}\boldsymbol{\varepsilon}_{ij})_p = \mathbf{d}\lambda \cdot \frac{\partial \mathbf{g}}{\partial \sigma_{ij}}$$

Where $\mathbf{d}\lambda$ is the proportionality constant known as the plastic multiplier, this equation is referred to as the flow rule. When $\mathbf{g}$ is different than $\mathbf{F}$ the material is said to follow a non-associated plasticity model, distinguishing between a yield function and a plastic potential function. However, the relation $\mathbf{F} \equiv \mathbf{g}$ holds a particular significance in plasticity theory; in this case, it is known as associated plasticity, and the material is considered "standard Applying the consistency condition.

$$\mathbf{dF} = \left\{ \frac{\partial \mathbf{F}}{\partial \boldsymbol{\sigma}} \right\} \cdot \mathbf{d}\boldsymbol{\sigma} + \left\{ \frac{\partial \mathbf{F}}{\partial \kappa} \right\} \cdot \mathbf{d}\kappa = 0$$

Where $\mathbf{d}\kappa$: the hardening parameter

After developing and arranging the various terms, the elastoplastic relationship between stress increments and strain increments is obtained as:

$$\mathbf{d}\boldsymbol{\sigma} = \left[\mathbf{D}^e - \frac{\mathbf{D}^e \cdot \left\{ \frac{\partial \mathbf{g}}{\partial \boldsymbol{\sigma}} \right\} \left\{ \frac{\partial \mathbf{F}}{\partial \boldsymbol{\sigma}} \right\} \mathbf{D}^e}{-\left\{ \frac{\partial \mathbf{F}}{\partial \kappa} \right\} \cdot \left\{ \frac{\partial \mathbf{g}}{\partial \boldsymbol{\sigma}} \right\} + \left\{ \frac{\partial \mathbf{F}}{\partial \boldsymbol{\sigma}} \right\} \cdot \mathbf{D}^e \cdot \left\{ \frac{\partial \mathbf{g}}{\partial \boldsymbol{\sigma}} \right\}} \right] \cdot \mathbf{d}\boldsymbol{\varepsilon} \quad \text{Or simply} \quad \mathbf{d}\boldsymbol{\sigma} = \mathbf{D}^{ep} \mathbf{d}\boldsymbol{\varepsilon}$$

$\mathbf{D}^e$: is the elastoplastic constitutive matrix

This relationship between stress increments $\mathbf{d}\boldsymbol{\sigma}$ and strain increments $\mathbf{d}\boldsymbol{\varepsilon}$, defines the transition from the elastic state to the elastoplastic state, which is characterized by a reduction in stiffness once the stress threshold is exceeded.

2-2- Failure Criterion

A failure criterion is represented by a yield function, which may incorporate strain hardening. In this study, a Mohr-Coulomb type criterion is adopted. This criterion states that failure occurs according to the following relation: $|\tau| = \mathbf{f}(\boldsymbol{\sigma})$. This relation can be expressed in the form of:

$$\mathbf{F}(\boldsymbol{\sigma}) = (\sigma_1 - \sigma_3) - (\sigma_1 + \sigma_3) \cdot \sin(\varphi) - 2 \cdot c \cdot \cos(\varphi) = 0$$

This corresponds to the equation of a plane, whose intersection with the hydrostatic axis ($\sigma_1 = \sigma_2 = \sigma_3$) occurs at the point defined by $H = -c \cdot \cot g \varphi$. Where $\sigma_1 > \sigma_2 > \sigma_3$, c : is the cohesion et φ : is the internal friction angle. The generalization of the Mohr-Coulomb criterion in the three-dimensional stress space results in the equation of a pyramid with a non-uniform hexagonal base (the failure surface), whose axis is

aligned with the hydrostatic axis. The Mohr-Coulomb criterion is often employed in soil behaviour modelling due to its simplicity and because its parameters have clear physical meaning. However, this criterion has certain limitations, such as singularities at the corners of the pyramid (i.e. discontinuities in the yield surface at specific stress combinations).

2-3- Alternative Form for Numerical Calculation

To facilitate numerical implementation, it is particularly convenient to rewrite the yield function in terms of the stress invariants. The main advantage of this formulation is that it allows coding the yield function and the flow rule in a more general form, requiring only the specification of three constants for each failure criterion. The principal stresses $\sigma_1, \sigma_2, \sigma_3$ are expressed in terms of the stress invariants as follows:

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \end{Bmatrix} = \frac{2(J_2)^{\frac{1}{2}}}{\sqrt{3}} \begin{Bmatrix} \sin\left(\theta + \frac{2\pi}{3}\right) \\ \sin\theta \\ \sin\left(\theta + \frac{4\pi}{3}\right) \end{Bmatrix} + \frac{I_1}{3} \begin{Bmatrix} 1 \\ 1 \\ 1 \end{Bmatrix} \quad \text{Where } \sigma_1 > \sigma_2 > \sigma_3 \quad \text{et} \quad -\pi/6 < \theta < \pi/6.$$

I_1 : the first invariant of the total stress tensor, J_2 : the second invariant of the deviatoric stress tensor, θ : a parameter defined by the Lode angle $\sin(3\theta) = -3\sqrt{3}J_3/2(J_2)^{3/2}$, which replaces J_3 the third invariant of the deviatoric stress tensor.

The Mohr-Coulomb failure criterion can thus be reformulated in terms of I_1, J_2 et θ . After substituting the principal stresses, the expression becomes:

$$F(I_1, J_2, \theta) = \frac{1}{3}I_1 \sin \varphi + (J_2)^{\frac{1}{2}} \left(\cos \theta - \frac{1}{\sqrt{3}} \sin \theta \cos \varphi \right) - c \cos \varphi = 0$$

In order to evaluate the elastoplastic constitutive matrix $\mathbf{D}^{ep}$, it is necessary to express the flow vector $\{\mathbf{a}\}^T$ in a form more suitable for numerical computation.

$$\{\mathbf{a}\}^T = \frac{\partial F}{\partial \sigma} = \frac{\partial F}{\partial I_1} \frac{\partial I_1}{\partial \sigma} + \frac{\partial F}{\partial (J_2)^{\frac{1}{2}}} \frac{\partial (J_2)^{\frac{1}{2}}}{\partial \sigma} + \frac{\partial F}{\partial \theta} \frac{\partial \theta}{\partial \sigma} \quad \text{Where} \quad \{\sigma\}^T = \{\sigma_x, \sigma_y, \sigma_z, \tau_{xy}, \tau_{yz}, \tau_{zx}\}.$$

This formulation allows for a more flexible and efficient implementation of the yield criterion and the flow rule within a finite element analysis code.

3- INTERFACE ELEMENT CONCEPT

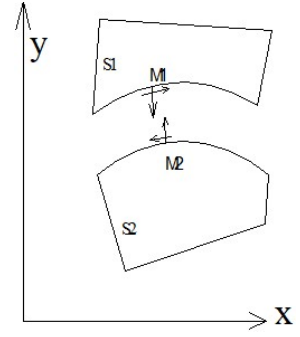
Interface elements were first introduced by Goodman et al. (1968) for the numerical analysis of rock masses. They were soon extended to the study of soil-structure interaction by several researchers such as Zienkiewicz et al. (1991), Ghaboussi et al. (1973), Desai et al. (1984), among others. In a two-dimensional case, the stress-displacement relationship for an interface element is expressed as:

$$\begin{Bmatrix} \sigma_n \\ \tau \end{Bmatrix} = \begin{pmatrix} \mathbf{K}_n & 0 \\ 0 & \mathbf{K}_s \end{pmatrix} \begin{Bmatrix} \mathbf{V}_r \\ \mathbf{U}_r \end{Bmatrix} = [\mathbf{C}] \begin{Bmatrix} \mathbf{V}_r \\ \mathbf{U}_r \end{Bmatrix}$$

Where σ_n, τ : are the normal and shear stresses;

$\mathbf{K}_n, \mathbf{K}_s$: are the normal and tangential stiffnesses;

$\mathbf{V}_r, \mathbf{U}_r$: are the relative normal and tangential displacements.



In this study, a thin-layer type interface element was adopted, based on the formulation by Desai et al. (1984). This is an eight-node element with a given thickness t . The major advantage of this element type is that it can be integrated into a finite element code without requiring additional special functions, such as Lagrange multipliers or penalty functions. It is treated like any other solid finite element, with the difference being in the constitutive matrix formulation. The constitutive matrix for this element is:

$$[\mathbf{C}]_i = \begin{bmatrix} \mathbf{C}_{nn} & \mathbf{C}_{nt} \\ \mathbf{C}_{tn} & \mathbf{C}_{tt} \end{bmatrix}$$

Where : $\mathbf{C}_{nn}$; $\mathbf{C}_{tt}$: are the normal and tangential stiffness components

$\mathbf{C}_{tn}$: The matrix includes coupling effects between normal and tangential behaviors if required.

The element stiffness matrix for the interface element is then assembled as:

$$[\mathbf{K}]_i = \int_v [\mathbf{B}]^T [\mathbf{C}^{ep}] [\mathbf{B}] dv$$

$[\mathbf{B}]$: is the strain-displacement matrix; $[\mathbf{C}^{ep}]$: is the elastoplastic constitutive matrix specific to the interface behaviour.

The integration is performed over the element's volume, this allows for a realistic simulation of the contact behaviour between materials with very different mechanical properties (such as concrete and soil) under various loading conditions.

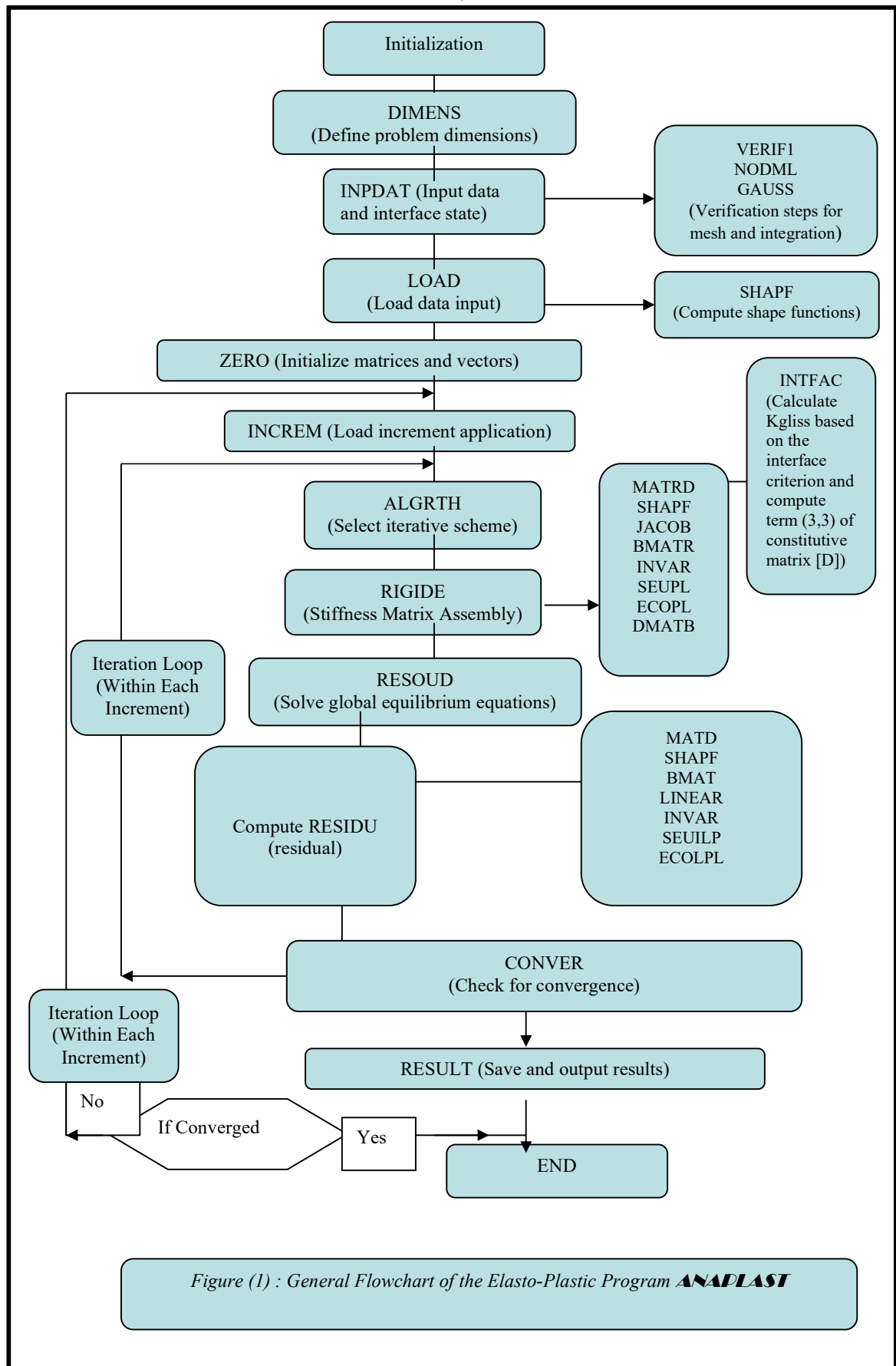


Figure (1) : General Flowchart of the Elasto-Plastic Program **ANAPLAST**

4- APPLICATION

Drawing inspiration from full-scale experimental results of a single bored pile installed through a multilayered soil profile, conducted by the School of Engineering of São Carlos, University of São Paulo in Brazil (Marilza et al., 2001), as well as numerical results obtained by LCPC (using the CESAR code), a numerical modeling of soil–pile behavior was performed using the ANAPLAST code. Two cases were considered: simulation with and without interface elements under axial loading in both tension and compression.

Since the pile studied is cylindrical with a circular cross-section and is axially loaded, the modeling can be carried out under axisymmetric conditions. In our case, the four soil layers and the pile were modeled using eight-node quadratic elements. The dimensions of the mesh domain were chosen such that the lateral boundary is located at a distance of $60r_0$ (where r_0 is the pile radius). The lower boundary is positioned at a depth of $1.94 l$ below the pile tip (where l is the pile length).

❖ **Present study:** Number of nodes: 198 and number of elements: 55

❖ **LCPC study:** Number of nodes: 242 and number of elements: 70

The constitutive behaviour adopted for the different soil layers is an associated elastoplastic model, with a Mohr-Coulomb failure criterion. An implicit scheme is used to integrate the constitutive law. The model parameters for each soil layer used in this study are summarized in Table (1).

Tableau (1): Table 1: Model parameters for the different soil layers.

Parameters	Depth of sampling (m)			
	1 ^{er} Layer (0 à 6.3)	2 ^{eme} Layer (6.3 à 8.3)	3 ^{eme} Layer (8.3 à 11)	4 ^{eme} Layer (11 à 20.6)
$E(kPa)$	9150	13510	13570	19300
ν	0.12	0.12	0.07	0.05
$C(kPa)$	13	12	14	17
$\phi(deg\ rés)$	26	23	23	23

The boundary conditions are defined as follows: zero horizontal displacements on the lateral boundary and along the axis of symmetry, and zero vertical displacements at the base.

The behaviour of the pile was modelled under the same experimental conditions used in the full-scale tests, for both types of axial loading: compression and tension. The characteristics of the pile are: diameter 0.35 m, length 7 m, Young's modulus $E = 17.3 \times 10^3$ MPa (in Tension), et $E = 29.9 \times 10^3$ MPa (in Compression) and Poisson's ratio $\nu = 0.3$. The axial load is applied through variable increments.

a) Study of Pile Behavior in Compression

Figures 2-a and 2-b illustrate the variation of the compressive force at the pile head as a function of vertical displacement, for both cases with and without interface elements.

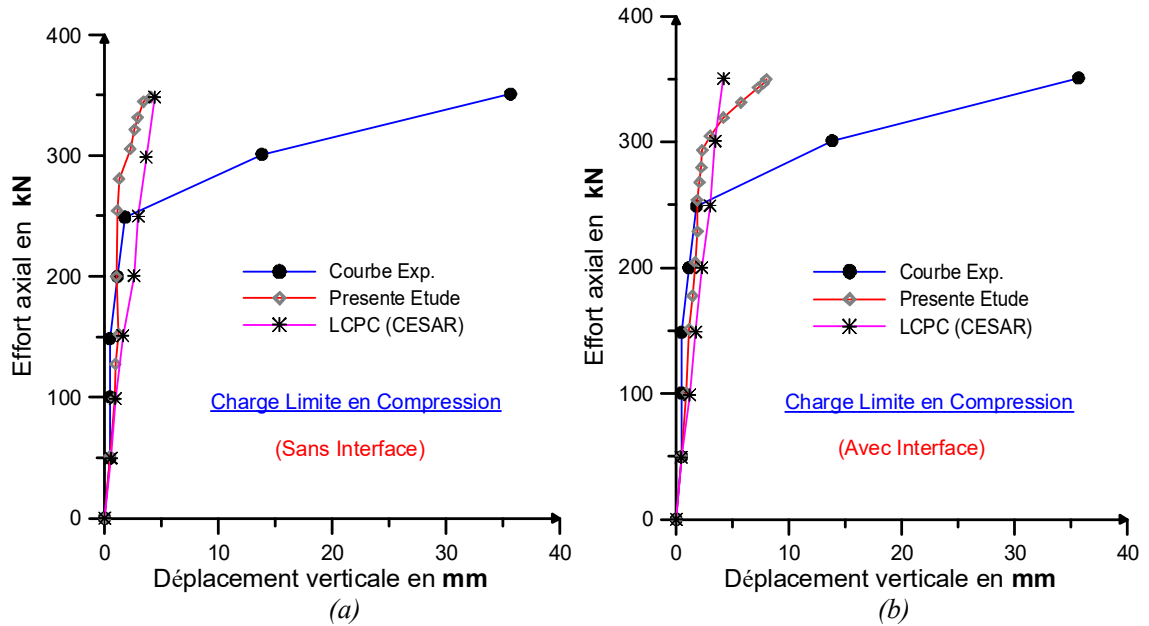
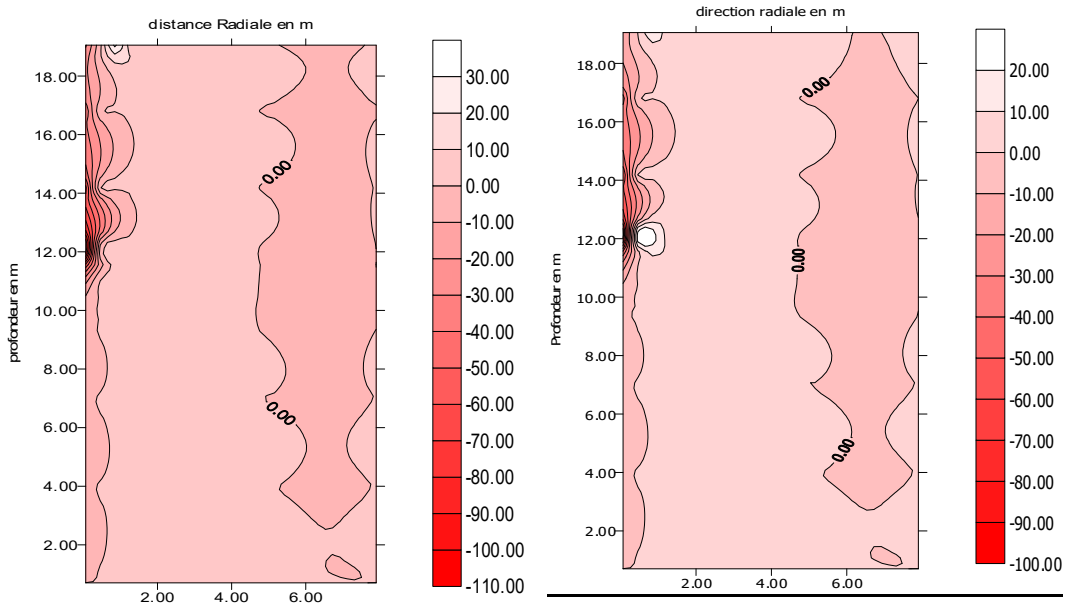


Figure (2) : Axial compressive force versus vertical displacement at the pile head.

The examination of the load–displacement curves shows that, in the linear portion, both numerical analyses exhibit good agreement with the experimental results. The ultimate pile load, approximately $P_{lim} = 350$ KN, is correctly predicted. However, this load is reached at significantly lower displacements compared to the experimental results. In this study, the modelling incorporating interface elements produces a curve with a characteristic elastoplastic response in the post-elastic region.

Figures 3-a and 3-b show the contours of axial compressive stresses (for cases without and with interface elements, respectively)



a) Without interface

b) With interface

Figure (3) : Contour plots of axial stresses σ_{zz} à 99% at 99% of the total compressive load.

From these figures, it can be observed that plastic yielding initiates at the pile tip in both cases (with and without interface elements) and progressively spreads upward along the pile shaft. Furthermore, the plastic zones obtained at the end of the calculation remain relatively limited in extent, concentrated near the pile shaft, while a large portion of the surrounding soil mass remains within the elastic domain. It can also be noted that the effect of the interface elements on the distribution of vertical stresses is relatively less significant.

b) Study of Pile Behaviour in Tension

Figures 4-a and 4-b present the variation of the axial force at the pile head as a function of its vertical displacement, for the two cases: with and without interface elements. From these figures, it is evident that our program accurately simulates the soil behaviour, even in the vicinity of failure — which is not the case in the study published by LCPC, where the behaviour remains linear up to failure. The analysis shows that the load–displacement curves from our study, especially with interface elements, exhibit a shape similar to that observed in the full-scale test. However, the ultimate load is somewhat underestimated ($P_{lim} = 300$ kN), which we believe is due to the significant effect of friction under tensile loading.

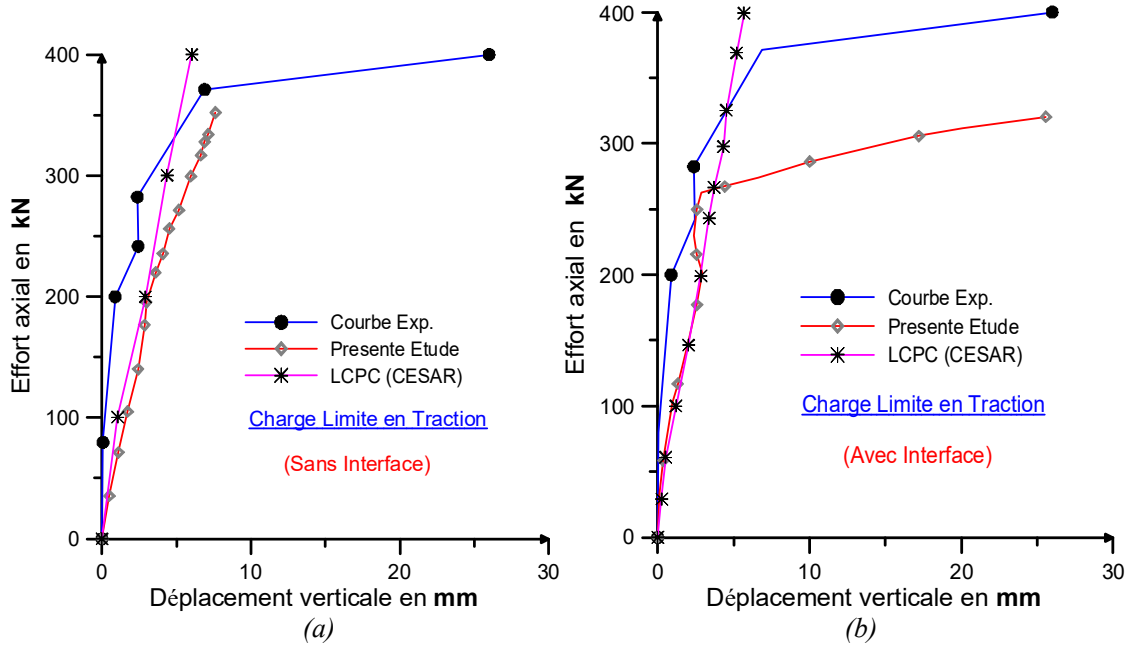


Figure (4) : Axial tensile force versus vertical displacement at the pile head.

Figures 5-a and 5-b display the contours of axial stresses for the tensile case (with and without interface elements, respectively).

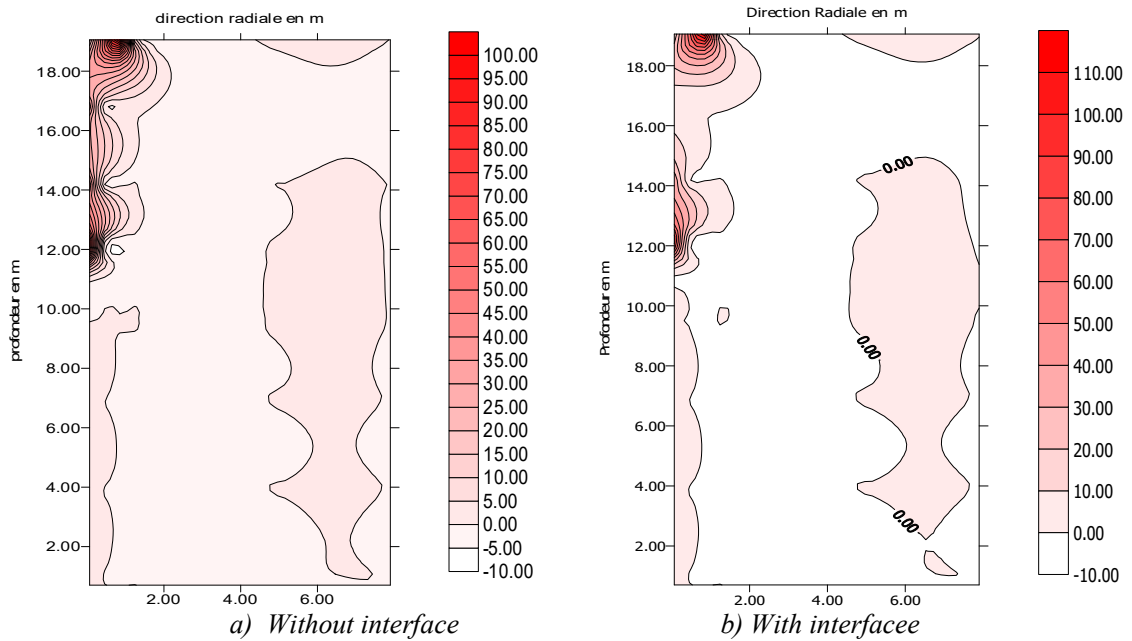


Figure (5) : Contour plots of axial stress σ_{zz} at 99% of the total tensile load.

The plastic zones develop initially at the pile tip and then spread toward the ground surface. Moreover, it is observed that the affected zone extends along the entire pile

shaft in the case of a perfect bond (without interface elements), while in the case with interface elements, this plastic zone is mainly localized at the pile head and tip. This behavior is likely due to the fact that relative slip between the soil and the pile is prevented in the perfect bond case, thereby mobilizing a larger amount of shaft friction along the pile.

5- CONCLUSION

Through this study, a modelling of the elastoplastic behaviour of geo-materials was presented, taking into account the contact conditions between two materials with significantly different stiffnesses (concrete–soil). The following conclusions can be drawn:

- The initial slope of the load–displacement curve depends primarily on the elastic properties of the soil.
- The ultimate load obtained using our computational program is comparable to that provided by experimental results for the various cases considered.
- The stiffness of the interface does not significantly affect the overall behaviour of the soil; however, it influences the transfer of forces between the two media and the stress distribution within the contact zone.

Finally, the numerical modelling of the elastoplastic behaviour of geo-materials is highly delicate, and achieving convergence in the iterative process is difficult. It depends on both the increment size and the degree of nonlinearity in the constitutive relations. It is recommended for future research to adopt automatic sub-stepping iterative schemes to improve stability and convergence.

REFERENCES

- DRUCKER “Soil mechanics and Work hardening theories of plasticity” ASCE, Vol, 122, 1957, pp. 338-346.
- DESAI C. S., ZAMAN M.M., LIGHTNER J.G. et SIRIWARDANE “Thin-layer element for interface and joints”. Int .Jour for Numerical and analytical Method in Geom. Vol. 8 , 1984 , pp 19-43.
- GENS, A., CAROL I. et ALONSO E. E. “ An interface of soil reinforcement interaction” Computers and Geotechnics, 1988, pp133-151.
- GHABOUSSI J., WILSON E.L et ISENBERG J. “finite element for rock joints and interfaces” –journ of soil Mech and Found Division, Vol, 99 , N° SM10, October 1973, pp 833-848.
- GOODMAN R. E., TAYLOR R.L et BREKKE T.L “A model for rock joints and interfaces” journal of the soil Mechanics and foundations Division, Vol , 94 N° SM3, May 1968, pp.637-659.
- MARILZA D. N., MESTAT P., FRANK R., DEGNY E. “Etude du comportement des pieux forés” Bulletin LCPC N° 231 /Mars-Avril 2001- pp 55-67.
- OWEN DRJ. et HINTON.E “finite element in plasticity theory and practices” Pincridja Press, Swensea, 1980.
- SALENCON J. “théorie de la plasticité pour les applications à la mécanique des sols” Éditions Eyrolles.
- ZEINKIEWICZ O.C. “la méthode des éléments finis appliquée à l’art de l’ingénieur”, 1973 Ediscience Paris.
- ZIENKIEWICZ O. C et TAYLOR R.I “The finite element method”, Volume 2, 4eme Edition, MC.Graw-Hill, London, 1991.

Contributions to the resolution of issues relating to the performance of fire extinguishing sprinkler systems (2)

Contribuții la rezolvarea unor problematici privind performanța sprinklerelor utilizate în stingerea incendiilor (2)

Lucian-Vasile Mihoc¹, Ștefan Dună¹, Andrei Dună¹, Cosmina Carmen Florica¹

¹ University Politehnica Timișoara
Piata Victoriei No. 2

E-mail: mihoc.lucian@gmail.com, stefan.duna@upt.ro, andrei.duna@student.upt.ro, cosmina.florica@upt.ro

DOI: 10.37789/rjce.2026.17.3.3

Abstract. *This paper presents an in-depth experimental and analytical study focused on evaluating the performance of sprinkler systems used in fire suppression. The research explores the interaction between droplet distribution, droplet velocity, kinetic energy, and their role in effective fire control. Various measurement and evaluation methods were applied, including Laser Precipitation Monitors (LPM), image processing techniques, and multiple coefficients for distribution uniformity. The study also details a flexible and mobile experimental stand developed to test different types of sprinklers under controlled conditions. Conclusions are drawn based on data gathered from both field and laboratory conditions, offering practical recommendations for system configuration, operation, and optimization.*

Key words: *Fire suppression, sprinkler systems, droplet size, CFD simulations, performance evaluation*

1. Introduction

Designing and executing fire suppression systems that use sprinklers involves several complex challenges, such as extrapolating droplet behavior beyond the standardized test height, accounting for airflow disturbances, evaluating drop distribution in irregular geometries, and managing variable heat release rates. Due to the limitations of traditional full-scale fire testing, computational and instrument-based measurements now provide critical insights for improving sprinkler performance.

The article was received on 27.04.2025, accepted on 11.09.2026 and published on 22.09.2026

The first part of this article was published in Romanian Journal of Civil Engineering, Volume 17 (2026), Number 2

2. Experimental setup and methodologies

2.1. Description of the mobile experimental sprinkler stand

General dimensions:

- **Stand height:** 2000 mm (2 meters)
- **Stand width:** 2000 mm (2 meters)
- **Stand length:** 3000 mm (3 meters)
- **Base height:** 1000 mm (1 meter)
- **Total stand height:** 3000 mm (3 meters)
 - Note: Sprinkler head manufacturers provide spray cone diagrams for a height of 3 meters measured from the sprinkler nozzle.

Main structure:

- The stand is constructed from 2-inch zinc pipes, forming the main frame.
- Pipes are arranged vertically and horizontally to create a robust support for mounting sprinklers.
- It is a mobile structure with 4 wheels at the base.

Connections and fittings:

- The stand is equipped with threaded plugs of 1/2 inch and 3/4 inch, alternately placed for mounting sprinklers:
 - **1/2 inch threaded plugs:** 8 pieces
 - **3/4 inch threaded plugs:** 8 pieces
 - **2-inch connection for pumps** with parameters $Q = mc/h$ and $H = mH_2O$

Sprinkler configuration:

- Sprinklers are mounted on the threaded connections, evenly distributed across the stand.
- Two types of sprinklers are used on the top bar of the stand:
 - **Bronze sprinkler head down 1/2"; 68°C, K 80, STANDARD**
 - **Bronze sprinkler head down 3/4"; 68°C, K115, STANDARD**

Sprinkler distribution:

- Sprinklers are placed so that each connection supports one of the two types of sprinklers, ensuring uniform and alternating distribution:
 - 1/2" threaded plug -> Bronze sprinkler head down 1/2"
 - 3/4" threaded plug -> Bronze sprinkler head down 3/4"

Stand sections:

- The stand is divided into sections of 1000 mm in width and 3000 mm in length, creating a network of supports for the mounted sprinklers.

Experimental use:

1. Water distribution measurement:

- The stand allows simultaneous mounting and testing of multiple sprinklers to evaluate water distribution and performance under controlled conditions.
- Data can be collected on flow rate, operating pressure, and spray uniformity.

2. Flexible configuration:

- Due to the alternating 1/2-inch and 3/4-inch connections, the stand offers flexibility in changing and reconfiguring the types of sprinklers used.

3. Precise measurements:

- Collection containers (e.g., trays, precipitation cylinders) can be placed under each sprinkler to measure the volume and distribution of applied water.

4. Monitoring and analysis:

- The stand allows the installation of additional equipment, such as distrometers, to measure the size and number of droplets in the spray cone.

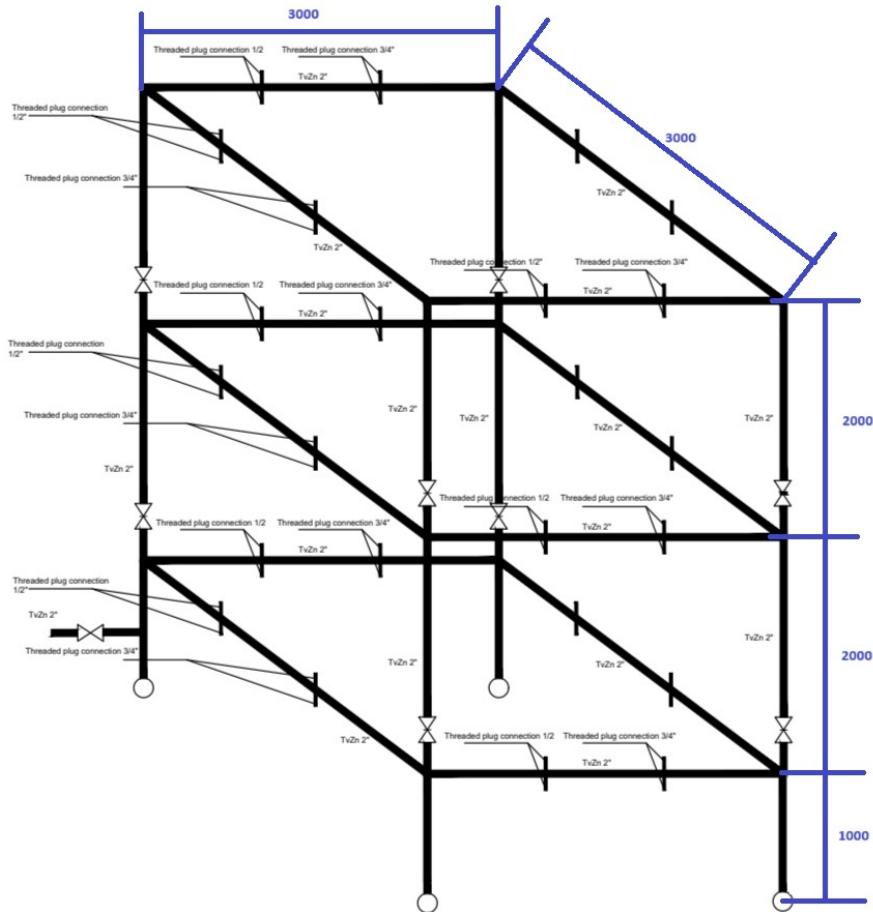


Fig. 1. Design of the experimental and research stand

Equipping the stand with sprinklers

For:

Bronze Sprinkler Head Down 1/2"; 68°C, K 80, STANDARD

General characteristics:

- Model: Pendent sprinkler, bronze.
- Connection Diameter: 1/2 inch.

- Operating Temperature: 68°C.
- K-Factor: 80 (metric units).

Flow characteristics:

- K-Factor: 80.
- Flow relationship: $Q=KP$

Where:

- Q is the water flow rate (l/min),
- K is the sprinkler coefficient (l/min·bar 0.5),
- P is the pressure at the sprinkler head (bar).

Example calculation:

- At 1 bar: $Q=80$ l/min.
- At 2 bars: $Q=113$ l/min.
- At 3 bars: $Q=139$ l/min.

Operating pressure:

- Typical operating pressure: between 1 and 3 bars (depending on manufacturer specifications).

Spray cone dimensions:

- Installation height (H): Depends on installation specifications and ceiling mounting height.
- Minimum spray cone section: Approximately 2-3 meters (standard height).
- Maximum spray cone section: Up to 4-5 meters (depends on operating pressure and system configuration).

Bronze Sprinkler Head Down 3/4", 68°C, K115, STANDARD

General Characteristics:

- Model: Pendent sprinkler, bronze.
- Connection diameter: 3/4 inch.
- Operating temperature: 68°C.
- K-Factor: 115 (metric units).

Flow characteristics:

- K-Factor: 115.
- Flow relationship: $Q=KP$

Where:

- Q is the water flow rate (l/min),
- K is the sprinkler coefficient (l/min·bar0.50.5),
- P is the pressure at the sprinkler head (bar).

Example calculation:

- At 1 bar: $Q=115$ l/min.
- At 2 bars: $Q=163$ l/min.
- At 3 bars: $Q=199$ l/min.

Operating pressure:

- Typical operating pressure: between 1 and 3 bars (depending on manufacturer specifications).

Spray cone dimensions:

- Installation Height (H): Depends on installation specifications and ceiling mounting height.
- Minimum spray cone section: Approximately 2-3 meters (standard height).
- Maximum spray cone section: Up to 4-5 meters (depends on operating pressure and system configuration).

These specifications often include performance graphs, spray distribution diagrams, and installation instructions, providing precise information about flow rate, pressure, and spray cone dimensions.

2.2. METHOD 1 Applied to the structure and design of the experimental stand

A detailed methodology is proposed to use the Christiansen Uniformity Coefficient (CUC) to evaluate the uniformity of water distribution in a trigger area Ad, specifically in the context of the stand.

Types of water collection containers:

- **Precipitation cylinders:**
 - Graduated plastic or glass cylinders used to measure the amount of water collected at a specific point.
- **Collection trays:**
 - Flat trays of various sizes used to collect and measure water distributed by sprinklers. These are typically made of waterproof materials and positioned in the field to capture sprayed water.
- **Collection cups:**
 - Small cylindrical containers placed at various measurement points to collect sprayed water.
- **Collection containers:**
 - Any type of container (e.g., plastic cups, jars) that can be used to collect and measure sprayed water.

Proper use of collection containers:

- **Positioning containers:**
 - Containers are placed in a dense matrix under the sprinkler spray area to capture variations in water distribution.
- **Measuring water:**
 - After collecting water, the volume of water in each container is measured to calculate the water depth (hi).

- **Data analysis:**

- With the collected data, the average water depth is calculated, and absolute deviations and the uniformity coefficient are determined.

Detailed methodology:

1. Experiment setup

Experimental stand:

- The 8 sprinkler heads are placed at the top of the stand according to the design.
- Sprinklers are positioned at established distances on the stand and mounted with heads down in the two types of 1/2 and 3/4 inch fittings on the top bar of the stand. All other fittings in the structure are sealed with plugs.
- The stand is connected to the pumping group to ensure minimum and maximum flow parameters Q and pumping height H, and to the water source to provide the water volume for at least 30 minutes at maximum flow and maximum operating pressure, considering linear, local losses, and geodetic height. A flow meter can be placed between the pumping group and the stand connection. A pressure gauge is mounted on one of the stand's top bars in a 1/2 inch fitting.

Measurement area:

- The measurement area under the experimental stand is established, considering that this is the area to be protected, covering the entire spray area of the 8 (4) sprinklers.
- Collection containers (e.g., collection boxes) are arranged in a dense matrix in this area, with a total surface area equal to the calculated spray area of the sprinklers' capacity, to capture droplets and variations in spray intensity from the overlapping spray cones of the sprinklers.
- Σ Base surface of boxes + Σ Spray surface of sprinklers in the cone sections corresponding to the protected area.

2. Measuring water distribution

Measuring water volume:

- The pumping group is started after verifying that the water source ensures the pumping flow. The system is filled and vented through an automatic vent or vent vessel placed at the top of the stand.
- All 8 (4) sprinkler heads are operated simultaneously, and water is collected in containers for a determined period (e.g., 30 minutes).
- The volume of water collected in each container/collection box is measured, and the water depth (h_i) is calculated at each measurement point.

3. Calculating average water depth

Average water depth:

- The average water depth (hm) is calculated using the formula:

$$h_m = \frac{1}{n} \sum_{i=1}^n (h_i) \quad (1)$$

Where:

- n is the number of collection containers.

4. Calculating absolute deviations

Absolute deviations:

- Absolute deviations from the average water depth:

$$|h_m - h_i| \quad (2)$$

are calculated for each measurement point.

5. Calculating Christiansen Uniformity Coefficient

Sum of absolute deviations:

- The sum of absolute deviations is calculated:

$$\sum_{i=1}^n |h_m - h_i| \quad (3)$$

Christiansen Uniformity Coefficient (CUC):

- The uniformity coefficient CUC is obtained using the relationship:

$$CUC = \left[1 - \left(\sum_{i=1}^n |h_m - h_i| \right) \times \frac{1}{n \times h_m} \right] \times 100\% \quad (4)$$

6. Additional considerations

Operating pressure and flow:

- The operating pressure for each type of sprinkler is checked and adjusted to ensure they function within specified parameters.

Data analysis:

- The uniformity of water distribution is analyzed to identify possible variations in the performance of different types of sprinklers.
- Based on the results, the experimental configuration is adjusted to improve performance if necessary.

Results analysis:

- All observations and obtained results are recorded, including calculated CUC values and any adjustments made.

2.3. METHOD 2 Applied to the structure and design of the experimental stand

In specialized literature, there are several methods like the Christiansen Uniformity Coefficient (CUC) for evaluating the uniformity of water distribution in sprinkler systems. One of the most common alternative methods is:

1. Heermann and Hein Uniformity Coefficient (CUH)

$$CUH = [1 - (\sum_{i=1}^n |h_i - hm|) / \sum_{i=1}^n h_i] \times 100\% \quad (5)$$

Where:

- h_i is the depth of water collected at point i ,
- hm is the average depth of water collected,
- n is the number of measurement points.

2. Distribution Uniformity Coefficient (DU)

The Distribution Uniformity Coefficient (DU) is used to evaluate the efficiency of distribution, specifically the intensity of spraying. The calculation formula for DU is:

$$DU = \frac{h_{min}}{hm} \times 100\% \quad (6)$$

Where:

- h_{min} is the average depth of water from the 25% of points with the lowest values,
- hm is the average depth of water collected.

3. Application Uniformity (UA)

Application Uniformity (UA) is like CUC and is used to evaluate the uniformity of water distribution over a sprayed area. The formula for UA is:

$$UA = [1 - (\sum_{i=1}^n |h_i - hm|) / \sum_{i=1}^n hm] \times 100\% \quad (7)$$

4. Coefficient of Variability (CV)

The Coefficient of Variability (CV) is used to measure the variability of the applied water depth. The formula for CV is:

$$CV = \frac{\sigma}{hm} \times 100\% \quad (8)$$

Where:

- σ is the standard deviation of the collected water depth,
- hm is the average depth of water collected.

5. System Performance Index (SPI)

The System Performance Index (SPI) is a complex measure that considers both the uniformity of water distribution and the efficiency of water application. SPI is defined as:

$$SPI = \frac{DU \times Ea}{100} \quad (9)$$

Where:

- DU is the Distribution Uniformity Coefficient,
- Ea is the efficiency of water application.

Calculating the efficiency of water application (Ea) in sprinkler systems for fire suppression is essential for evaluating system performance. By collecting and analyzing data on the volume of water applied and effectively used, the system's efficiency can be determined, and opportunities for performance improvement and risk reduction associated with fires can be identified.

3. Calculation methodology for application efficiency (Ea) in fire sprinkler systems

1. Defining Water Volumes:

- **Applied Water Volume (V_{applied}):** The total volume of water discharged by the sprinkler system during an operational cycle. This can be measured using water meters installed on the sprinkler supply system.
- **Effectively Used Water Volume (V_{utilized}):** The volume of water that actively contributes to extinguishing the fire or protecting surfaces from excessive heat. This can be determined through direct measurements and post-fire analyses.

2. Data Collection:

- **Applied Water Volume (V_{applied}):**
 - The test stand is equipped with a water meter or flowmeter to record the total volume of water used by the sprinkler system.
 - Alternatively, the total volume can be calculated based on the nominal flow rate of each sprinkler head and the operating time.
- **Effectively Used Water Volume (V_{utilized}):**
 - After the fire is extinguished or after the predefined experimental time, the affected areas are assessed to determine the efficiency of water use. This may include measuring residual water, or the amount collected in control zones.
 - In a real fire scenario, post-fire analysis and visual inspection help estimate the proportion of water that effectively contributed to controlling and extinguishing the fire.

3. Application Efficiency (E_a) calculation:

The application efficiency is calculated using the formula:

$$E_a(\%) = (V_{\text{utilizat}}/V_{\text{aplicat}}) \times 100 \quad (10)$$

Example calculation:

- Suppose that during one operational cycle, the sprinkler system discharged a total of 10.000 liters of water (V_{applied}).
- Post-event evaluation determined that 7,500 liters were effectively used for fire suppression and surface protection (V_{utilized}).

Thus, the application efficiency would be: $E_a (\%) = 75\%$

This means that 75% of the applied water was effectively used to control and extinguish the fire.

4. Factors influencing Application Efficiency (E_a):

1. **Distribution uniformity:** Non-uniform water distribution can result in over-irrigated and under-irrigated areas. Ensuring even water coverage significantly improves application efficiency.
2. **Pressure and flow rate:** Proper pressure and appropriate flow rate are essential for optimal sprinkler performance. Regular inspection and maintenance of these parameters can greatly impact efficiency.
3. **Interference and obstacles:** Furniture, equipment, or other physical barriers may obstruct or deflect water spray, reducing effectiveness. Proper space planning and arrangement can mitigate these issues.

4. **Sprinkler type and nozzle characteristics:** Selecting the appropriate sprinkler type and nozzle design for the specific application maximizes coverage and optimizes water use efficiency.

4. Methodology for using a disdrometer to evaluate sprinkler performance for fire suppression applications

Test stand:

- **Stand Dimensions:** Height: 2000 mm, Width: 2000 mm, Length: 3000 mm.
- **Types of sprinklers used:**
 - 4 units of Standard Bronze Pendent Sprinklers, 1/2", 68°C, K80.
 - 4 units of Standard Bronze Pendent Sprinklers, 3/4", 68°C, K115.
- **Sprinkler arrangement:** Sprinklers were alternately mounted on 1/2-inch and 3/4-inch threaded pipe fittings to ensure a uniform distribution of each type across the stand.

Disdrometer:

- Model Used: Optical disdrometer for droplet size and velocity measurement.

Methodological steps

1. Setting up the experimental stand:

- Install the eight sprinkler heads on the stand according to the specified layout and design.
- Ensure that each sprinkler is correctly connected to the water supply system and operates at the specified pressure.

2. Mounting the disdrometer:

- Position the disdrometer so it can measure the droplet size and velocity within a cross-section of the spray cone.
- Align the device carefully to accurately capture the necessary data.

3. Configuring and calibrating the disdrometer:

- Set up the disdrometer according to the manufacturer's instructions.
- Calibrate the device to guarantee precise measurements of droplet size and velocity.

4. Data collection:

- Operate the sprinklers at the specified pressure and flow rates.
- Measure droplet size and velocity at different heights and positions within the spray cone using the disdrometer.
- Record data on droplet size, number, and distribution in each cross-section.

5. Measurements at 1-meter intervals:

- Perform droplet size and velocity measurements at 1-meter intervals from the sprinkler heads.

- Document the disdrometer's angle and position at each measurement location.

6. Data filtering and analysis:

- Filter the collected data to eliminate errors caused by droplet coincidence and edge effects.
- Group droplet size measurements in 0.1 mm increments, ranging from 0.25 mm to 7.95 mm.
- Exclude droplets smaller than 0.2 mm in diameter.
- Eliminate droplets with velocities exceeding ± 2 standard deviations from the mean velocity measured for a given droplet size at a specific radial location.

7. Kinetic energy calculation:

- Calculate the kinetic energy of each droplet measured at each radial measurement location.
- The kinetic energy per unit volume of water applied (J/L) is obtained by dividing the cumulative kinetic energy of measured droplets by the total measured water volume.

8. Evaluation of droplet size distribution and kinetic energy:

- Compare the measured droplet size distributions with those obtained through alternative measurement methods.
- Calculate the average droplet size distributions and kinetic energy for each sprinkler type.

9. Fire Suppression applicability:

- Assess the uniformity of water distribution and the efficiency of spray coverage based on the kinetic energy transferred to the ground or protected surfaces.
- Determine whether the sprinkler type and setup provide adequate and uniform coverage for effective fire suppression.

10. Documentation and reporting:

- Record all observations, measurements, and calculated results.
- Prepare a comprehensive report including conclusions regarding the sprinkler system's performance and recommendations for improvements.

This detailed methodology leverages a disdrometer to evaluate the performance of sprinklers used for fire suppression purposes. It provides accurate data regarding droplet size and velocity, enabling precise calculation of the kinetic energy transfer—an essential factor in ensuring efficient and uniform coverage during firefighting operations.

5. Methodology for using imaging systems to evaluate sprinkler performance for fire suppression applications

Test Stand:

- **Stand dimensions:** Height: 2000 mm, Width: 2000 mm, Length: 3000 mm.

- **Types of sprinklers used:**
 - 4 units of Standard Bronze Pendent Sprinklers, 1/2", 68°C, K80.
 - 4 units of Standard Bronze Pendent Sprinklers, 3/4", 68°C, K115.
- **Sprinkler arrangement:** Sprinklers were alternately mounted on threaded pipe fittings of 1/2 inch and 3/4 inch, ensuring an even distribution of each sprinkler type across the stand.

Imaging systems:

- High-speed cameras for capturing images of water droplets within the sprinkler spray cone.
- Specialized image analysis software for measuring droplet size and distribution based on the captured images.

Methodological steps

1. Setting up the experimental stand:

- Install the eight sprinkler heads on the test stand according to the design and specifications provided.
- Ensure that each sprinkler is properly connected to the water supply and operates at the designated pressure.

2. Installing and configuring the imaging system:

- Position the high-speed cameras to capture clear images of the droplets within the spray cone of each sprinkler.
- Align the cameras correctly to cover different cross-sections of the spray pattern.
- Adjust camera settings (e.g., recording speed, resolution) to obtain high-quality images of the droplets.

3. Data collection:

- Operate the sprinklers at the specified pressure and flow rates.
- Capture images of the droplets at different heights and positions within the spray cone.
- Ensure that images cover multiple sections to provide a comprehensive view of droplet distribution.

4. Measurements at 1-meter intervals:

- Capture images at intervals of 1 meter from the sprinkler heads.
- Document the camera position and angle at each measurement location.

5. Image analysis:

- Analyze the captured images using image processing software to measure droplet size and distribution.
- Filter the data to remove artifacts and measurement errors.
- Group the droplet size measurements into 0.1 mm increments for detailed analysis.

6. Kinetic energy calculation:

- Calculate the kinetic energy of each measured droplet based on its size and estimated velocity.

- Compute the kinetic energy per unit volume of water applied (J/L) by dividing the total kinetic energy by the measured water volume.

7. Evaluation of droplet size distribution and kinetic energy:

- Compare the measured droplet size distributions with those obtained from other measurement methods.
- Calculate the mean droplet size distributions and kinetic energy for each sprinkler type.

8. Fire suppression applicability:

- Evaluate the uniformity of water distribution and the effectiveness of spray coverage based on the kinetic energy transferred to the ground or protected surfaces.
- Determine if the sprinkler configuration and type provide adequate and uniform coverage for effective fire suppression.

9. Documentation and reporting:

- Record all observations, measurements, and calculated results.
- Prepare a comprehensive report including conclusions on sprinkler system performance and recommendations for improvements.

Specific details for using imaging systems

Principle of imaging systems:

- High-speed cameras capture moving droplets within the sprinkler spray cone.
- Images are processed using specialized software to measure droplet size and distribution.
- The data provide an accurate characterization of droplet size and dispersion patterns.

Recommended equipment:

- High-Speed Cameras: For capturing sharp images of moving droplets.
- Image Analysis Software: For precise measurement of droplet size and distribution.

Following the analysis and measurements, the results confirmed that the droplet distribution complies with the specifications outlined in Table 1.

The calculations were carried out in tabular form based on the measurements taken from Sprinkler Head 1 at an operating pressure of $P = 1$ bar, recorded every 5 minutes up to 30 minutes. The results are presented in Table 1.

The absolute deviations range between 0.5 mm and 3.25 mm, which are relatively small compared to the average depth, suggesting that the water distribution in the four trays is very uniform. This uniformity is essential for fire suppression systems, as a homogeneous water distribution across the entire protected area helps reduce temperatures and prevent the spread of fire. The largest deviations occur at t6

(30 minutes), when the total water volume is at its maximum. Even under these conditions, the distribution remains uniform, indicating reliable system performance in scenarios with higher water flow rates.

Table 1.

Calculating the Christiansen Uniformity Coefficient (CUC)

Measurement Time	Water Depth in Tray 1-h1 [mm]	Water Depth in Tray 2-h2 [mm]	Water Depth in Tray 3-h3 [mm]	Water Depth in Tray 4-h4 [mm]	Average Water Depth - hm [mm]	Calculation of Absolute Deviations from the Average Water Depth				Sum of Absolute Deviations	Christiansen Uniformity Coefficient (CUC) [%]
						Tray Deviation 1 [mm]	Tray Deviation 2 [mm]	Tray Deviation 3 [mm]	Tray Deviation 4 [mm]		
$t_0 = 0$ min	0	0	0	0	0	0	0	0	0	0	100
$t_1 = 5$ min	44	42	45	43	43,5	0,5	1,5	1,5	0,5	4,0	97,70
$t_2 = 10$ min	89	85	87	90	87,75	1,25	2,75	0,75	2,25	7,0	98,00
$t_3 = 15$ min	133	131	130	135	132,25	0,75	1,25	2,25	2,75	7,0	98,68
$t_4 = 20$ min	178	179	175	173	176,25	1,75	2,75	1,25	3,25	9,0	98,72
$t_5 = 25$ min	222	220	223	225	222,5	0,5	2,5	0,5	2,5	6,0	99,33
$t_6 = 30$ min	267	261	264	263	263,75	3,25	2,75	0,25	0,75	7,0	99,34

The CUC values, ranging from 97.70% to 99.34%, demonstrate a good uniformity of water distribution, which is essential for an effective fire suppression system. A high CUC suggests that water is evenly dispersed in all directions, reducing the risk of leaving certain areas uncovered. This very good uniformity indicates that at a pressure of 1 bar, the sprinkler effectively covers the protected area, ensuring that the entire surface receives an adequate amount of water to control or extinguish a fire.

6. Conclusions

This methodology employs advanced imaging systems to evaluate the performance of sprinklers specifically designed for fire suppression applications. By utilizing high-speed cameras and image analysis software, the method enables the precise measurement of droplet size and distribution within the sprinkler spray cone. Accurate data regarding droplet size and distribution are critical for ensuring efficient and uniform water coverage during fire suppression operations. Uniform distribution improves the sprinkler's ability to suppress fires effectively, minimizing unprotected zones and optimizing the use of water resources. Furthermore, by analyzing droplet characteristics, it becomes possible to better understand the dynamics of water dispersion, which directly influences the kinetic energy transferred to the protected surfaces — a key factor in fire control efficiency.

Through detailed image-based evaluation, this approach provides valuable insights for selecting, configuring, and improving sprinkler systems to enhance their real-world performance. Ultimately, the use of imaging systems supports the design of safer, more reliable fire suppression strategies by ensuring that sprinklers deliver water where it is most needed, with the appropriate energy and coverage.

References

- [1] NFPA 13: *Standard for the Installation of Sprinkler Systems*, National Fire Protection Association, current edition.
- [2] Pahl, Joseph M., Wendt, Bruce: *Discharge Distribution Performance for an Axisymmetric Model of a Fire Sprinkler Head*, Fire Safety Journal, Vol. 14, pp. 101-111, 1988.
- [3] Huang, J.C.P.: *Break-up of Axisymmetric Liquid Sheets*, J. Fluid Mech., Vol. 43, Part 2, pp. 305-319, 1970.
- [4] Wendt, Bruce, Pahl, Joseph M.: *Discharge Distribution for an Axisymmetric Model of a Fire Sprinkler Head*, NBS-GCR-86-517, National Bureau of Standards, Gaithersburg, MD, 1986.
- [5] Chigier, N.A.: *The Physics of Atomization*, ICLASS-91 Proceedings, National Institute of Standards and Technology, Gaithersburg, MD, pp. 1-15, 1991.
- [6] Krishnan, G., Gakkar, R.P., Prakash, S.: *Water Droplet Evaporation in Fire Plumes*, ICLASS-91 Proceedings, National Institute of Standards and Technology, Gaithersburg, MD, pp. 97-104, 1991.
- [7] Yao, Cheng: *Overview of Sprinkler Technology Research*, 5th Conference Proceedings of the International Association of Fire Safety Scientists.
- [8] E.R. Galea: *Predicting the Performance of Fire Sprinkler Systems Using Computational Fluid Dynamics*, Journal of Fire Sciences, Vol. 18, No. 4, pp. 237-263, 2000.
- [9] Dlugogorski, B., Lucas, D.: *The Influence of Water Drop Size on the Effectiveness of Sprinkler Systems*, Fire Technology, Vol. 36, pp. 1-19, 2000.

Indoor Air Quality and Associated Health Effects. Current Perspectives

Calitatea aerului interior și efectele asupra sănătății. Perspective actuale

Cristian Păcurar¹, Adriana Tokar¹, Marius Adam¹

¹ Politehnica University of Timisoara, Romania

Traian Lalescu 2, Timisoara 300223, Romania

E-mail: cristian.pacurar@upt.ro, adriana.tokar@upt.ro, marius.adam@upt.ro

Abstract: *The relation between air quality and human health is one of the most well-documented contemporary public health topics and this is determined by the interaction between air pollutants and the body's physiological systems.*

Key words: indoor air quality, ambiental comfort, thermal comfort, productivity, performance, environmental quality

DOI: 10.37789/rjce.2026.17.3.4

1. Introduction

Indoor comfort is a determining factor for our physical and mental health, considering that we spend approximately 90% of our time in indoor spaces. The quality of the air we breathe indoors has a direct and immediate impact on our well-being [1]. Health effects are usually divided into two categories: short-term and long-term. Short-term effects often occur after a single or prolonged exposure to stale air (for example, a whole day in an unventilated office). Symptoms are like those of a cold, irritation of the nose, throat and eyes, sneezing, coughing or feeling of suffocation. Or for example, dryness, itching or irritation may occur on the skin, especially if the humidity is below 30%. Also, at the neurological level, dizziness, headaches, chronic fatigue and difficulty concentrating may occur. All these symptoms define the "Sick Building Syndrome", and the health condition improves rapidly as soon as the person leaves the building. Long-term effects are given by constant exposure to indoor pollutants can be much more severe, because toxic substances accumulated in the body. Examples are chronic respiratory diseases (e.g. worsening of asthma, development of bronchitis or other obstructive pulmonary diseases). As cardiovascular problems occur when fine particles (PM2.5) can pass from the lungs directly into the bloodstream, increasing the risk of hypertension or

heart disease [2]. Severe allergic reactions can also occur, such as constant exposure to mold spores or dust mites, and then permanent allergies can be triggered. Another major risk is prolonged exposure to gases such as radon or volatile chemical compounds (benzene, formaldehyde). The goal is to have the cleanest air possible in the rooms to have optimal efficiency of the activities of the individuals in those.

From a technical and functional point of view, improving the indoor space is based on optimizing the interior environment, not only in terms of aesthetics, but also the performance of buildings in relation to human biology. This paper will show how each of the points mentioned above can be improved.

2. Content of the paper

The optimization of the interior environment can be done through air quality optimization (e.g. ventilation and purification), sustainable design and materials, the quality of lighting, acoustics, as well as the functionality of the space.

Optimizing air quality is the most important part where you can improve the quality of life in the indoor space and below are some points where you can intervene. You can intervene by controlling humidity, maintaining relative humidity between 40-60%, so that mold growth will decrease and limit the survival of airborne viruses. Another method of intervention is through active purification, using purifiers with HEPA H13 filters and layers of activated carbon (for absorbing gases and odors). Another way to optimize air quality is through heat recovery (HRV/ERV), replacing natural ventilation with mechanical systems that filter outside air and recover thermal energy, simultaneously eliminating volatile organic compounds [3].

Improving the interior space can also be done at the design level and the materials used for construction, because the integration of natural elements has the role of reducing cortisol. It can be done through vegetative integration by painting the walls green or adding indoor plants (e.g. *Sansevieria Trifasciata*, *Spathiphyllum*, *Chlorophytum Comosum*, *Dracaena*) which, although they have a limited purification effect on a large scale, significantly improve the mental state. Also can be used materials with low emissions, and by selecting finishes (furniture, paints, adhesives,) with Low VOC or Formaldehyde Free certifications, "indoor pollution" will be prevented [2].

The quality of lighting is another factor, because light adjusts the biological rhythm, so having biodynamic lighting, you can increase the quality of the interior space, and this is achieved by installing LED systems that change their color temperature throughout the day: cold light in the morning to inhibit melatonin and warm light in the evening. Another way is to maximize natural light, using reflective surfaces and glazed areas reduce dependence on artificial sources [4].

Acoustic comfort plays an important role, as background noise is a major factor of physiological stress. This can be achieved through sound-absorbing treatments, i.e. by using acoustic panels, carpets or porous materials to reduce the reverberation time. Acoustic comfort can also be achieved through noise insulation; to attenuate structural sounds specific membranes are added under the floor.

The functionality of the space consists of adapting the space to the dimensions and movements of the human body. This is achieved by using smart thermostats to create micro-climates adapted to the activities in each room. Functionality can also be achieved by adding adjustable furniture to the spaces, namely sit-stand desks and chairs with active lumbar support to prevent musculoskeletal disorders [4].

A summary of what was written above can be found in Table 1.

Table 1

Summary on the optimization of the interior environment

Environmental Parameter	What to optimize?	How to optimize?
Thermal	Humidity and Temperature	Maintain 20-22°C and 40-60% humidity. Use plants to naturally regulate humidity.
Visual	Natural vs. Artificial Light	Place the desk perpendicular to the window. Use warm light (2700K) for relaxation and neutral (4000K) for work.
Acoustic	Sound Absorption	Add soft materials (carpet, thick curtains) to eliminate echo and reduce background noise.
Olfactory/Air.	Air Quality (CO ₂)	Ventilate (5-10 min) three times a day or install a purifier with a particle sensor.

If we look at all the factors we have discussed (thermal, lighting, visual, acoustic and air quality), the one that has the main role for environmental comfort is, without a doubt, thermal comfort, immediately followed by air quality. As an interaction of these factors, we can say that Thermal comfort is the central factor, because it is very important how the human body reacts instantly to temperature variations. Even if there is light or silence in the room, if the individual is too cold or too hot, then he cannot concentrate on the activity he is carrying out. Reason why he does not give maximum efficiency. Moreover, to maintain an ideal balance it is necessary that the temperature of the walls and windows be close to the air temperature to avoid the discomfort of the cold sensation. On the other hand, even if there is an ideal temperature in a room and the CO₂ level is high, then we have stale air, which most of the time leads to a decrease in the ability to concentrate by up to 40%. This decrease in concentration is often accompanied by drowsiness, headaches, and malaise. However, if the humidity is not within normal parameters and is at a critical level, then we can be in a situation where the air is too humid, and mold appears or when it is too dry and the mucous membranes become irritated [1]. All of this is related to the quality of the air in a room. To optimize a room, we must ensure that fresh air can be breathed in, that heat is not lost from the room. Then that there is adequate light depending on the time of day, and only then that the room has adequate acoustics and that background noise does not increase. As a result of what is presented above, we can say that thermal comfort is the "basic pillar" because it directly affects

others, a better visibility of the hierarchy of importance on well-being can be seen in Figure 1.

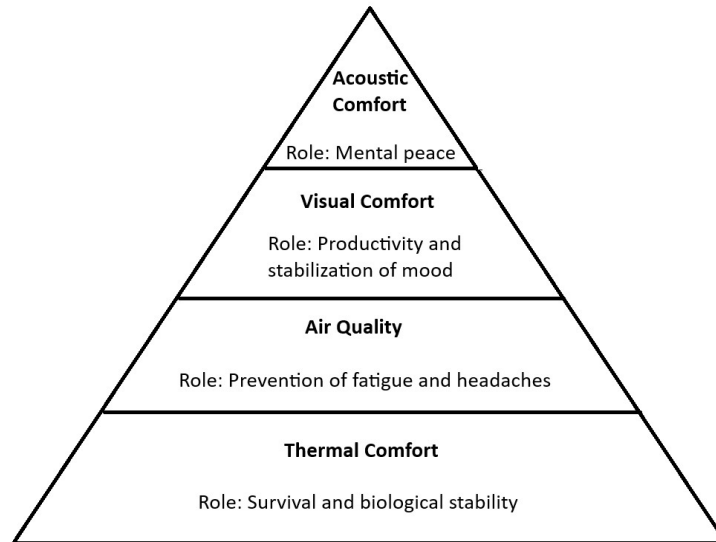


Fig. 1. The hierarchy of importance of factors that optimize the indoor environment

To optimize a room, the first step is to invest in temperature control (insulation, thermostat, efficient radiators) and ventilation, as these ensure an optimal impact on well-being.

3. Conclusions

Indoor air quality is not just an environmental factor, but a critical determinant of health, which is why it needs to be at a high level so that people can have advanced productivity. The thermal comfort is the main pillar who influence the productivity of people and influences the other factors.

References

- [1] I. Sârbu, C. Păcurar, „Performanța energetică a clădirilor și confortul ambiental”, Editura Politehnica, Timișoara, 2016.
- [2] I. Sârbu, C. Păcurar, „Sisteme de încălzire și răcire a clădirilor”, Editura Politehnica, Timișoara, 2015.
- [3] EEA (2022a), NMVOC: non-methane volatile organic compounds; NOX: nitrogen oxides; PM2.5: particles with a diameter smaller than 2,5 microns; PM10: particles with a diameter smaller than 10 microns; SO2: sulphur dioxide.
- [4] C. Pacurar, A. Tokar, M. Adam, „Key factors to have a good sleep quality in bedrooms”, Revista Română de Inginerie Civilă, Volumul 15 , Numărul 4, 2024.

The influence of ventilation on CO₂ concentration, compared to the requirements of the I5/2022 regulation

Influența ventilației asupra concentrației de CO₂, raportat la cerințele normativului I5/2022.

Florin-Vladimir Mihailov¹, Grațiela-Maria Țârlea²

¹ Technical University of Civil Engineering.

Bd. Lacul Tei nr. 122 - 124, cod 020396, Sector 2, Bucharest, Romania

E-mail: florin-vladimir.mihailov@phd.utcb.ro, gratiela.tarlea@gmail.com.autor

DOI: 10.37789/rjce.2026.17.3.5

Abstract: *The standard for the design, execution, and operation of ventilation and air conditioning installations, indicative of I5/2022, establishes four indoor air quality categories for the occupied area of civil premises. For residential civil buildings, the main source of pollution is bio-effluents emitted by humans. This article presents the result of measuring the CO₂ concentration values recorded in three buildings during the period when there were no users. The analysis of the recorded results does not show any causal links between the way ventilation is performed, through infiltration through leaks or mechanical ventilation with heat recovery, and the variation in indoor CO₂ values.*

Key words: ventilation, CO₂ concentration, indoor air quality

1. Introduction

A building is in use when the occupants carry out various residential or professional activities and it is necessary to ensure bioclimatic conditions, and it is in standby when there are no users in the building, but the bioclimatic conditions must be maintained at a higher level of energy efficiency.

Indoor air quality is the most important component in ensuring a healthy living environment; it is determined by a control based on real-time monitoring of the operation of heating, ventilation, and air conditioning systems.

To manage the quality of the living environment and evaluate the performance of technical systems, it is necessary to know the values of pollutants, including CO₂ concentration. [1].

Although in residential constructions the main CO₂ polluter is human presence, there are other potential sources that generate CO₂ emissions such as the construction

materials from which the walls are made, the materials from which the furniture is made, the utility installations, the combustion of fuels for food preparation, etc. [2].

The literature focuses on monitoring and evaluating bio-effluent emissions generated by occupants/users [3], [4], [5], [6], [7], [8], [9], without identifying the value of CO₂ emissions generated by other potential sources [2].

This article analyzes the CO₂ emissions monitored in three buildings without users, buildings built in different periods, part of a condominium but also independent homes, made of established materials but also of earth and straw, with ventilation with recovery but also ventilation through infiltration through leaks.

2. Methods

The CO₂ concentration measurements were taken in actual living rooms and compared with the regulations mentioned earlier.

This indicates that when conclusions are drawn regarding the indoor climate, a satisfactory indoor climate is defined based on the presented regulations.

2.1 Description of the houses studied;

2.1.1. Passive apartment Bucharest.

The construction, completed in 1976 (see Figure 1), is part of a condominium consisting of 47 apartments. It is situated on the 10th floor of a 12-story building, at an elevation of 33 meters above ground level.

The condominium features a reinforced concrete frame structure with a BCA envelope.

In 2023, the building underwent thermal rehabilitation, which involved the application of a 10 cm thick layer of mineral wool with a thermal conductivity of $\lambda = 0.036 \text{ W/(m}\cdot\text{K)}$.

Although the apartment originally had two bedrooms and a living room, it was reconfigured by transforming the kitchen into bedroom 3 and moving the cooking and food preparation activities to the balcony.

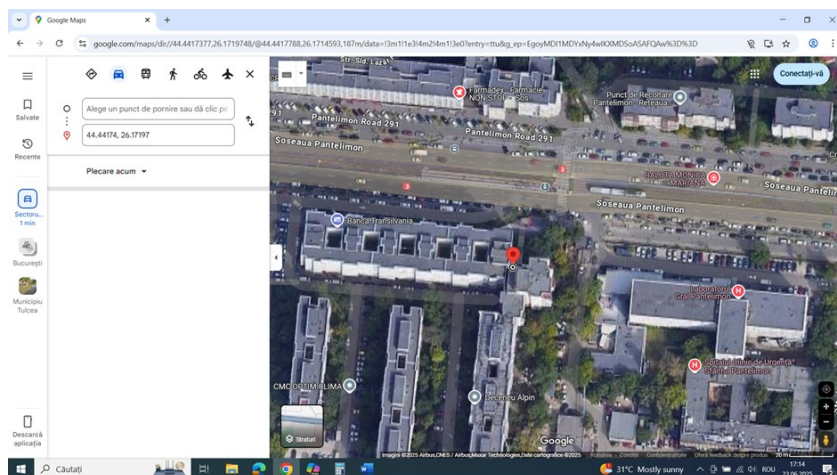


Fig. 1. "Passive" apartment location Bucharest

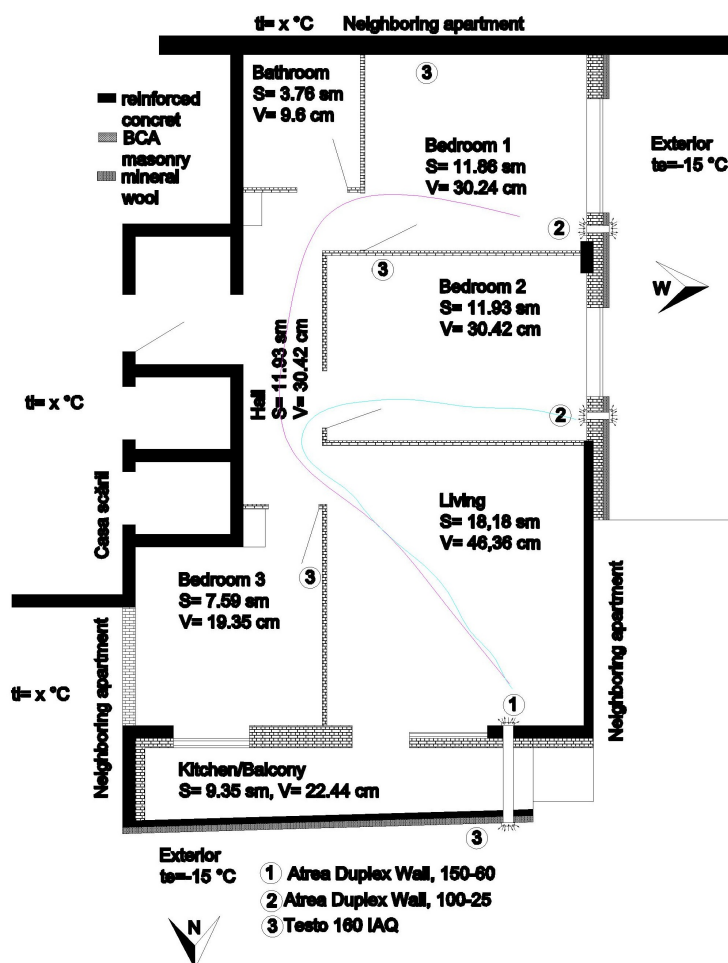


Fig. 2. Passive apartment Bucharest

Permanently inhabited by 4 people, of above average build, the apartment benefits from three ventilation units with alternating flow heat recovery with ceramic heat storage element positioned as follows:

- Atrea Duplex Wall 100-25, 2 units, each with a capacity of 25 m³/h, located in bedroom 1 and bedroom 2.
- Atrea duplex Wall 100-60, 1 unit with a capacity of 60 m³/h, located in the living room.
- The internal volume of heated air is 189 m³.
- Total volume of ventilated air 110 m³/h.
- Nominal air flow rate per person 27.5 m³/h.
- Hourly number of ventilated air changes 0.582.

2.1.2. N-zeb House Varasti, Calaras County

The construction is carried out in the period 2020-2024, located in the town of Vărăști, Călăraș County, Figure 3. The resistance structure is made of reinforced concrete frames with porotherm brick masonry with a thickness of 38 cm and a mineral wool thermal system with a thickness of 10 cm and thermal conductivity $\lambda = 0.036 \text{ W}/(\text{m}\cdot\text{K})$. The construction complies with the minimum resistance requirement for N-zeb construction, according to the MC001/2022 normative.

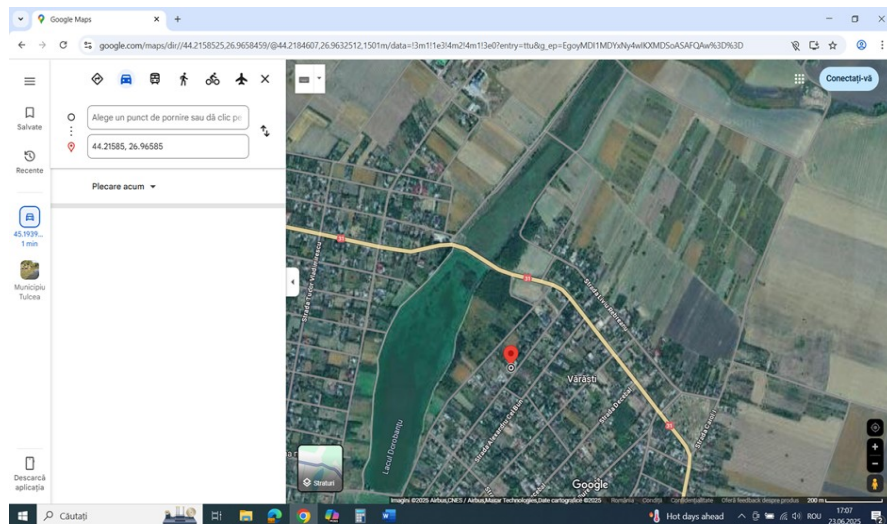
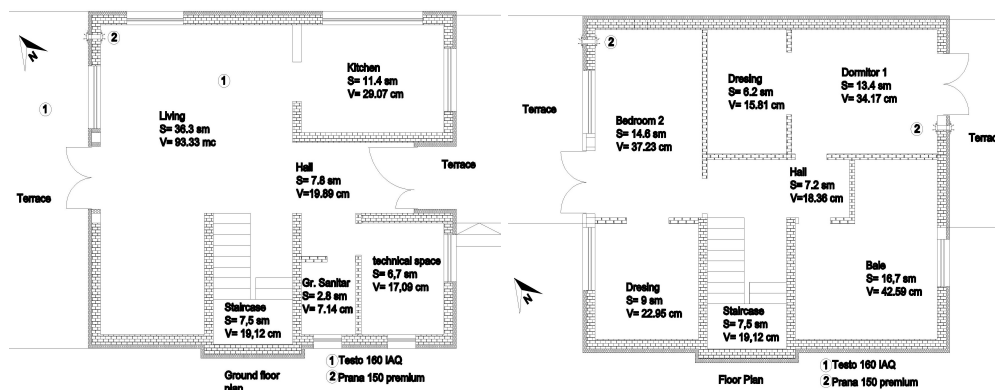


Figure 3. N-Zeb house location Varasti, Calarasi county

Home used during holidays and weekends; the maximum number of users is 3. It is equipped with 3 (three) Prana 150 premium-type countercurrent recovery ventilation units, the ventilation flow rate being 30 m³/h for each unit. These are located in the bedrooms upstairs and in the living room on the ground floor (Figure 4).

The influence of ventilation on CO₂ concentration, compared to the requirements of the I5/2022 regulation



(a) (b)
Fig. 4. N-Zeb House Vărăști, Călăraș County
(a) ground floor plan, (b) first floor plan

- The internal volume of heated air is 356.51 m³.
- Total volume of ventilated air: 90 m³/h.
- Nominal air flow rate per person 30 m³/h.
- Number of hourly ventilated air changes 0.246.

2.1.3. Ecological house, Slava Rusă, Tulcea county.

Located in Slava Rusă, Tulcea County, Figure 5. the construction is made on a wooden structure with masonry made of unburnt bricks made of clay mixed with wheat straw (adobe). Figure 6. Collective memory identifies the year of construction as before 1900.

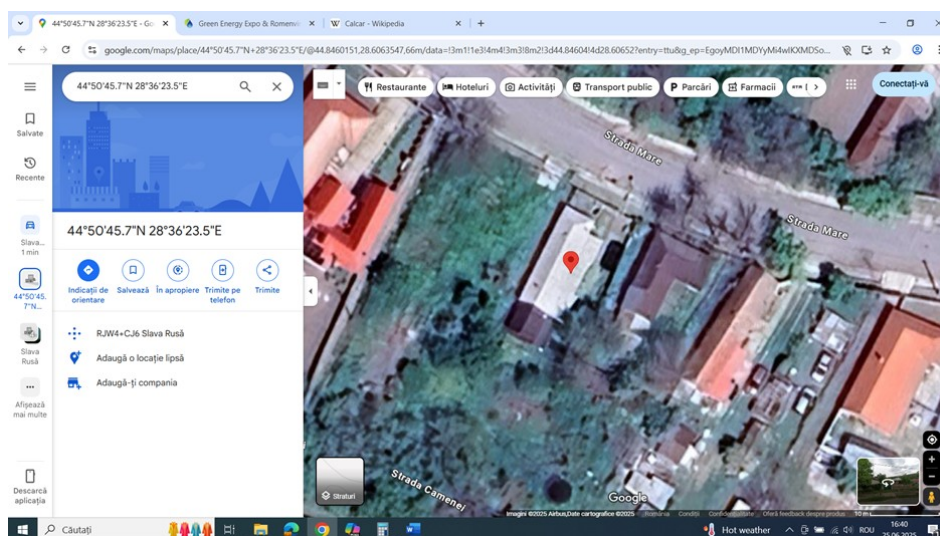


Fig. 5. Ecological house location, Slava Rusă, Tulcea county

The property is inhabited exclusively during the holiday period.



Fig. 6. Ecological house Slava Rusă, Tulcea county

2.2 Description of the Testo 160 IAQ measuring device

Table 1

Testo 160 IAQ measuring device	
Temperature Measurement	
Measurement range	0 to +50 °C
Accuracy	± 0.5 °C
Resolution	0.1 °C
Humidity Measurement	
Measuring range	0 to 100 %RH
Accuracy	±2 %RH la +25 °C <80 %RH
	±3 %RH la +25 °C > 80 %RH
	±1 %RH hysteresis
	±1 %RH / year drift
Resolution	0.1% RH
CO ₂ measurement	
Measuring range	0 to 5,000 ppm
Accuracy	±(50 ppm + 3 % of m.v.) at +25 °C
	Without external power supply: ±(100 ppm + 3 % of m.v.) at+25 °C
Resolution	1 ppm
Pressure Measurement	
Measuring range	600 to 1100 mbar
Accuracy	±3 mbar at+22 °C
Resolution	1 mbar

The testo 160 IAQ is a WiFi data logger with display and integrated sensors for; temperature, humidity, and atmospheric pressure. [10]The equipment was purchased through a doctoral grant offered by the Doctoral School of the Technical University of Civil Engineering in 2022.

3. Measurement results

3.1. Passive apartment Bucharest

The apartment is permanently inhabited. For the measurements, the apartment was vacated for a short vacation..

The monitored period during which the users did not live in the building is between 31.12.2024 9:00 a.m. and 02.01.2025 4:00 p.m.

The period considered for the evaluation is between 01.01.2025 12:00 and 02.01.2025 12:00. Figure 7.

CO₂ concentrations were monitored in each bedroom. The recorders were placed in areas of the room where they were not directly exposed to the ventilated air stream.

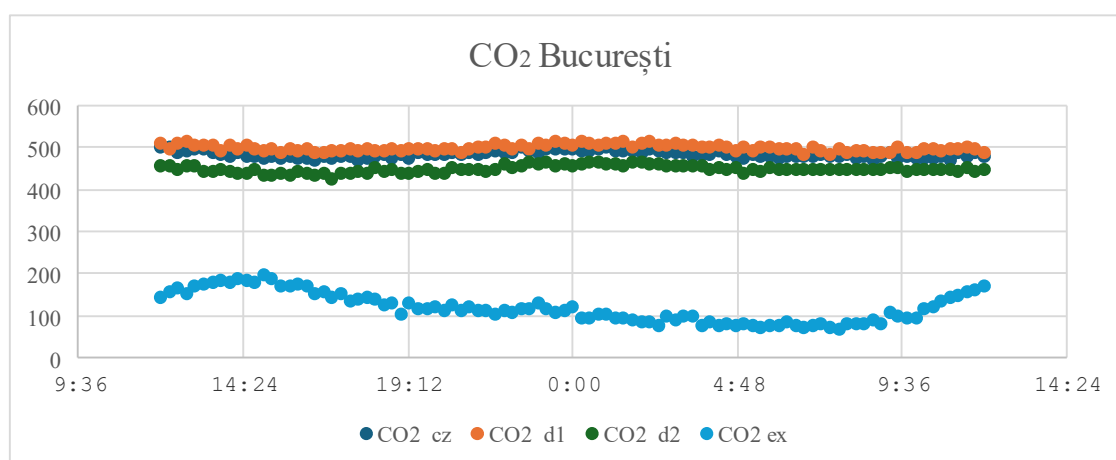


Fig. 7. CO₂ values, passive apartment Bucharest

3.2. House N-zeb Varasti Calarasi County

The house is used during holidays and weekends from Friday 2:00 PM to Sunday 2:00 PM. The monitored period taken into account is 28.01.2025 12:00 PM and 29.01.2025 12:00 PM.

CO₂ concentration values were monitored in the living room located on the ground floor of the building. Figure 8.

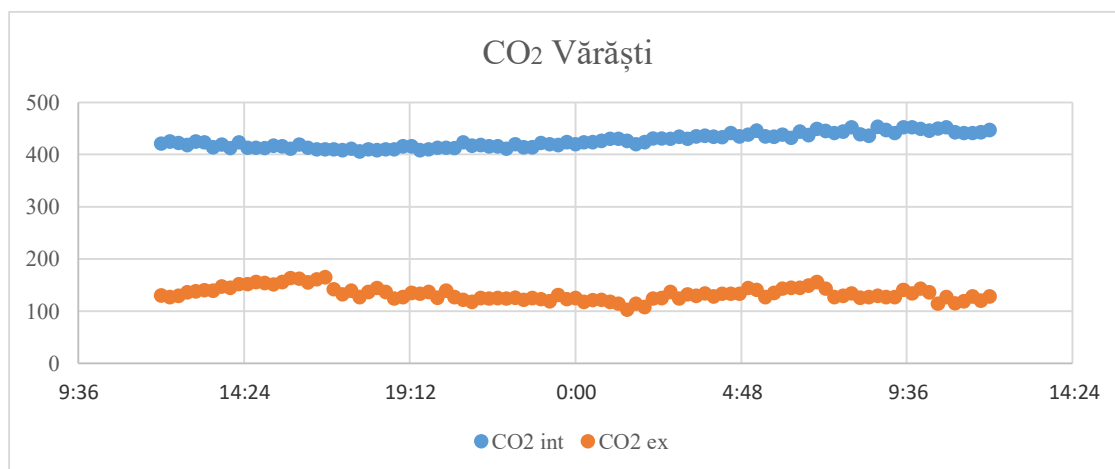


Fig. 8. CO2 values, N-Zeb house, Varasti

3.3. House N-zeb Varasti Calarasi County

The house is used mainly in the summer.
The recorded values are shown in Figure 9.

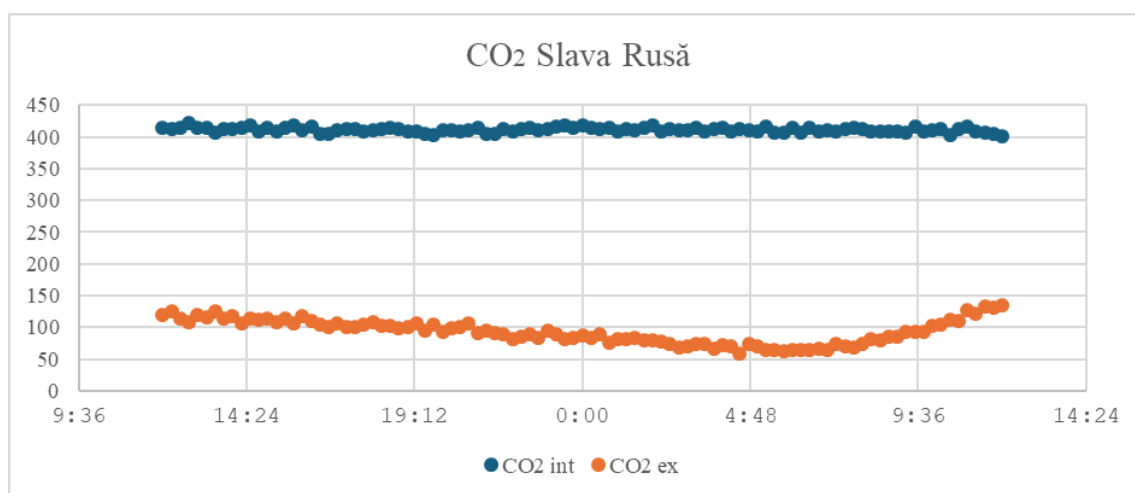


Fig. 9. CO2 values, ecological house Slava Rusă

4. Discussion

Chapter 2 of the Norm for the design, execution, and operation of ventilation and air conditioning installations, Indicative I 5 – 2022, establishes four indoor air quality categories (IDA1 – IDA4), mentioned in Table 2.

Thus, for civil buildings where the main source of pollution is bio-effluents emitted by humans, the classification into IDA categories is done depending on the purpose of the building, the activity in the rooms, the type of pollution sources, and the

The influence of ventilation on CO₂ concentration, compared to the requirements of the I5/2022 regulation rooms where smoking is not allowed and is classified according to the CO₂ concentration accepted in the indoor air, above the outdoor concentration, Table 2.1.1.2, page 15 of I5/2022. [11], Table 2.

Table 2

Indoor air quality class	CO2 values above the outdoor air level, [ppm]	
	Supported domain	Default value
IDA 1 High indoor air quality	≤ 400	350
IDA 2 Average indoor air quality	400 – 600	500
IDA 3 Moderate indoor air quality	600 – 1000	800
IDA 4 Poor indoor air quality	≥ 1000	1200

By applying the default values presented in Table 2 to the average values recorded during the monitoring period, the reference values for establishing the air quality level are obtained. For IDA1, the values are presented in Table 3; for IDA2, the values are presented in Table 4; for IDA3, the values are presented in Table 5; and for IDA4, the values are presented in Table 6.

Table 3

		Average value	Default value	Reference value
		measured	IDA 1	IDA 1
		[ppm]	[ppm]	[ppm]
BUCHAREST MEASUREMENT	CO2 cz	483	350	833
	CO2 d1	498	350	848
	CO2 d2	448	350	798
	CO2 ex	120	350	470
SLAVA RUSĂ MEASUREMENT	CO2 int	411	350	761
	CO2 ex	93	350	443
VĂRĂȘTI MEASUREMENT	CO2 int	427	350	777
	CO2 ex	133	350	483

Table 4

		Average value	Default value	Reference value
		measured	IDA 2	IDA 2
		[ppm]	[ppm]	[ppm]
BUCHAREST MEASUREMENT	CO2 cz	483	500	983
	CO2 d1	498	500	998
	CO2 d2	448	500	948
	CO2 ex	120	500	620
SLAVA RUSĂ	CO2 int	411	500	911

		Average value	Default value	Reference value
		measured	IDA 2	IDA 2
		[ppm]	[ppm]	[ppm]
MEASUREMENT	CO2 ex	93	500	593
VĂRĂȘTI	CO2 int	427	500	927
MEASUREMENT	CO2 ex	133	500	633

Table 5

		Average value	Default value	Reference value
		measured	IDA 3	IDA 3
		[ppm]	[ppm]	[ppm]
BUCHAREST MEASUREMENT	CO2 cz	483	800	1283
	CO2 d1	498	800	1298
	CO2 d2	448	800	1248
	CO2 ex	120	800	920
SLAVA RUSĂ MEASUREMENT	CO2 int	411	800	1211
	CO2 ex	93	800	893
VĂRĂȘTI MEASUREMENT	CO2 int	427	800	1227
	CO2 ex	133	800	933

Table 6

		Average value	Default value	Reference value
		measured	IDA 4	IDA 4
		[ppm]	[ppm]	[ppm]
BUCHAREST MEASUREMENT	CO2 cz	483	1200	1683
	CO2 d1	498	1200	1698
	CO2 d2	448	1200	1648
	CO2 ex	120	1200	1320
SLAVA RUSĂ MEASUREMENT	CO2 int	411	1200	1611
	CO2 ex	93	1200	1293
VĂRĂȘTI MEASUREMENT	CO2 int	427	1200	1627
	CO2 ex	133	1200	1333

5. Conclusion

From the analysis of the graphs of the measured values, Figure 7 for CO₂ measurements in Bucharest, Figure 8 for CO₂ measurements in Vărăști, and Figure 9 for CO₂ measurements in Slava Rusă, the following conclusions are highlighted:

1. The variation in indoor CO₂ concentration values is not influenced by the variation in outdoor CO₂ concentration.

2. The variation in the values recorded at the passive apartment in Bucharest indicates the influence of the CO₂ concentration in neighboring apartments through migration through the building elements.

The reference values resulting from the summation of the default value according to the specifications of the I5/2022 normative for IDA1 of 350 ppm, with the outdoor CO₂ concentration values, Table 3, for the three locations, are similar to the CO₂ concentration values recorded indoors, both for mechanically ventilated buildings with recovery and for buildings ventilated by infiltration through leaks. It is necessary to establish thresholds independent of other indoor or outdoor CO₂ concentration values.

Applying the default value of 1200 ppm, corresponding to low indoor air quality for IDA4, leads to the maximum acceptable level for CO₂ concentration in civil buildings, according to the NP 008-97 standard, of 1600 ppm.

The CO₂ concentration in a building that is on hold and/or unused is not influenced by the existence of heat recovery ventilation.

References

- [1] J. Kim, T Hong, M. Kong, K. Jeong, „Building occupants’ psycho-physiological response to indoor climate and CO₂ concentration changes in office buildings”, Building and Environment, Volume 169, February 2020,106596.
- [2] NORMATIV privind igiena compoziției aerului in spații cu diverse destinații, in funcție de activitățile desfășurate, in regim de iarna-vara; INDICATIV NP 008-97.
- [3] S. Park , D. Song, „CO₂ concentration as an indicator of indoor ventilation performance to control airborne transmission of SARS-CoV-2”, Journal of Infection and Public Health 16, 2023, pp. 1037–1044.
- [4] X. Lu , Z. Pang , Y. Fu , Z. O’Neill, „The nexus of the indoor CO₂ concentration and ventilation demands underlying CO₂-based demand-controlled ventilation in commercial buildings: A critical review”, Building and Environment 218, 2022, 109116.
- [5] Gabriel Rojas at all, ” Towards a harmonized database of indoor air contaminant concentrations: Methods and application to CO₂”, Building and Environment 292, 2026, 114297 .
- [6] Henry P. Oswin at all, „Using indoor CO₂ concentration thresholds to understand and improve the air quality of public buildings: A practical approach”, Energy & Buildings 347, 2025, 116254
- [7] B. Simanica, B. Nordquista, H. Bagge, D. Johansson, „Indoor air temperatures, CO₂ concentrations and ventilation rates: Longterm measurements in newly built low-energy schools in Sweden”, Journal of Building Engineering 25, 2019, 100827.
- [8] X. Liang, J. Shim, O. Anderton, D. Song, „Low-cost data-driven estimation of indoor occupancy based on carbon dioxide (CO₂) concentration: A multi-scenario case study”, Journal of Building Engineering 82, 2024, 108180,
- [9] G. S. Yerragolam at all, „Effect of airflow rate on CO₂ concentration in downflow indoor ventilation”, Indoor Environments 1, 2024, 100012.
- [10] <https://static.testo.com/image/upload/US/testo-160-iaq-datasheet-us.pdf> /27.08.2025/ 16.33
- [11] Normativ pentru proiectarea, executarea și exploatarea instalațiilor de ventilare și climatizare, Indicativ I 5 – 2022.

High-porosity cellular glass made by microwave heating with a liquid expanding agent

Sticlă celulară de porozitate ridicată fabricată prin încălzire cu microunde cu un agent de expansiune lichid

Lucian Paunescu¹, Sorin Mircea Axinte², Bogdan Valentin Paunescu³

¹Daily Sourcing & Research SRL

27a Prof.dr. Mihail Georgescu street, sector 2, Bucharest 024034, Romania

E-mail: lucianpaunescu16@gmail.com

²National University of Science and Technology "Politehnica", Faculty of Applied Chemistry and Materials Science

1-7 Gh. Polizu street, sector 1, Bucharest 011061, Romania

E-mail: sorinaxinte@yahoo.com

³Consitrans S.A.

56 Polona street, sector 1, Bucharest 010494, Romania

E-mail: pnschogdan@yahoo.com

DOI: 10.37789/rjce.2026.17.3.6

Abstract. *The work aimed at producing a high-porosity cellular glass, using a recipe composed of soda-lime-silica glass waste, borax as a fluxing agent, and aqueous KOH solution as an expanding agent. The heating process for sintering/foaming was based on microwave irradiation, a known unconventional technique, but practically not used in high-temperature applications until now. The results showed that density of $0.26 \text{ g}\cdot\text{cm}^{-3}$, thermal conductivity of $0.069 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, and compressive strength of 1.6 MPa were obtained, corresponding to the optimal variant. The work originality consists in the use of the liquid foaming agent and applying the own microwave heating technique.*

Key words: cellular glass, microwave, KOH solution, glass waste, high-porosity.

Rezumat. *Lucrarea a vizat producerea unei sticle celulare cu porozitate ridicată, utilizând o rețetă compusă din deșeuri de sticlă sodă-calciu-silice, borax ca agent de flux și soluție apoasă de KOH ca agent de expansiune. Procesul de încălzire pentru sinterizare/spumare s-a bazat pe iradierea cu microunde, o tehnică neconvențională cunoscută, dar practic neutilizată în aplicații la temperaturi înalte până în prezent. Rezultatele au arătat că s-a obținut densitatea de $0,26 \text{ g}\cdot\text{cm}^{-3}$, conductivitatea termică de $0,069 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ și rezistența la compresiune de 1,6 MPa, corespunzătoare variantei optime. Originalitatea lucrării constă în utilizarea agentului de spumare lichid și aplicarea tehnicii proprii de încălzire cu microunde.*

Cuvinte cheie: sticlă celulară, microundă, soluție de KOH, deșeu de sticlă, porozitate înaltă.

1. Introduction

According to the latest literature data [1], in 2022, the total packaging waste per inhabitant in EU countries reached 186.5 kg, of which 36.1 kg of glass packaging waste, representing 19 % of the entire amount of packaging waste. Thus, the total annual quantity of glass packaging waste generated in the EU reached 16 million tonnes, i.e. an impressive value. An increasing trend in the amount of glass waste is exhibited in the EU and also in the world, taking into account that the EU reported 15.2 million tonnes in 2019 [2].

Partially, recycled glass waste, either from post-consumer drinking bottles or from broken and replaced window glass in buildings, is already industrially reused in the traditional production of new glass, the operation being cost-effective in energy terms. However, a significant financial disadvantage is the technological necessity of colour sorting of recycled glass waste. This processing involves quite high costs [3].

A new trend regarding the use of this waste type has begun to be felt in the world in the last 3-4 decades, the waste being directed mainly towards the manufacture of alternative construction materials. In this application field, the glass quality imposed by its chemical composition (closely related to the colour of the initial material) is not a major requirement, what's important being the removal of contaminants (plastics, heavy metals, organic materials, etc.), washing and advanced grinding.

The production of materials with thermal insulation qualities (low weight, low heat conductivity, and high porosity) requires foaming the residual glass with an adequate expansion agent, incorporated into the waste matrix, by applying a heat process at high temperatures between 750-1150 °C [4].

Several companies from European countries (Austria, Belgium, Germany, the Czech Republic, Scandinavia), and the United States, joined by China due to the assimilation of current technologies, are at the forefront of the global market for cellular glass made from residual glass [5].

Various types of expanding agents are used in the industrial processes of manufacturing cellular glass: carbon products including coal, black carbon, glycerol, etc., carbonates/sulfates such as calcium carbonate, sodium carbonate, dolomite, gypsum, etc., carbides/nitrides including silicon carbide and silicon nitride [4].

The new millennium has promoted numerous small-scale experiments on the manufacture of cellular glass presented in the world literature. Various types of recycled glass waste have been tried, including also other species of silicate materials suitable for the production of foams intended for thermal insulation of buildings, such as: cathode ray tube [6], borosilicate glass [7], bituminous shale waste [8], metallurgical slag [9], zinc hydrometallurgy waste [10], quartz sand and coal gangue [11], and coal fly ash [12]. Also, different types of expanding agent have been tested,

such as: agents of vegetable origin [13, 14], eggshell [15], and agents of organic origin [16].

The experimental use of soda-lime-silica glass waste as raw material, borax as a fluxing agent and aqueous $\text{NaOH}\cdot\text{H}_2\text{O}$ solution as an expanding agent, in order to manufacture cellular glass, has been recently presented in the literature [14, 17]. The variation of the porosity aspect (from predominantly closed to predominantly open) was obtained by using different ratios between fluxing agent and expanding agent, which modified the density of the foamed material within very wide limits (between $0.16\text{--}0.79\text{ g}\cdot\text{cm}^{-3}$), while the porosity reached very high values (up to 92 %). The role of $\text{NaOH}\cdot\text{H}_2\text{O}$ consisted in reducing the density value as well as decreasing the proportion of closed porosity. The addition of borax associated with small proportions of $\text{NaOH}\cdot\text{H}_2\text{O}$ favoured the densification process and the creation of a closed-pore structure. Foaming the mixture based on glass waste was achieved due to the water vapor released by the thermal decomposition of the foaming agent. Corresponding to the glass transition temperature of $587\text{ }^\circ\text{C}$, a crystalline phase of hydrated sodium and calcium silicate ($\text{Na}_2\text{CaSi}_2\text{O}_6\cdot 2\text{H}_2\text{O}$) is formed. Upon reaching the softening point of the mixture containing the glass of over $700\text{ }^\circ\text{C}$, the release of water vapour from the crystalline phase mentioned above generates bubbles inside the viscous mass, which later turn into cells.

All industrial processes for manufacturing cellular glass, according to data provided in the literature, provide the thermal energy necessary for sintering the glass-based mixture using well-known conventional processes based on burning traditional fuels or electrical resistance heating.

The technique based on the application of the peculiarities of electromagnetic waves to convert their power as energy carriers into heat and its propagation in the mass of the material subjected to heating from the inside to the outside, in the opposite direction to conventional thermal processes, has been known since the middle of the 20th century. However, the interest of researchers was focused on other fields of application, in telecommunications and radar. The energetic properties, despite the remarkable efficiency of microwaves, did not arouse the interest of specialists. Practically, the only applications in this area were limited to industrial drying processes and heating processes at low temperatures.

However, researchers from the Romanian company Daily Sourcing & Research SRL have used the energy peculiarities of microwaves since 2016, achieving significant levels of energy efficiency in small-scale cellular glass manufacturing processes [18] compared to those of industrial processes known in the world.

The current paper includes a method for manufacturing microwave-assisted high-porosity cellular glass designed and tested on a small scale by the Romanian authors, which may contribute to the development of the mentioned technique. The original elements introduced in this work are the use of the foaming agent in the form of an alkaline KOH -based solution as well as the achievement of the thermal sintering/foaming process by unconventional microwave heating.

2. Methods and materials

2.1 Methods

As mentioned above, two important elements of originality characterized the current work: microwave heating in an own version and the choice of a liquid foaming agent not used in the cellular glass manufacturing process.

The sintering/foaming process of glass waste was based on heating the raw material under the influence of microwave irradiation as a particularly energy-efficient unconventional technique, applied by the authors in an original version consisting of predominantly direct and partially indirect heating by placing a protective screen made of microwave-susceptible materials in the form of a ceramic tube. This tube was positioned between the source emitting electromagnetic waves and the material to be heated. The method has the role of tempering the intensity of direct contact of waves with the material surface, which, in the case of glass, causes destruction of its internal structure. The wall thickness of the ceramic tube (of 2.5 mm) is essential for the irradiation process efficiency, being experimentally determined. The microwave flux is partially absorbed in the mass of the vertical tube wall, heating it quickly and efficiently. Predominantly, the flux penetrates the tube wall and comes into direct contact with the glass sample to be heated. In this way, the heating process is mixed: predominantly direct and partially indirect. The partially indirect heating is of the conventional type, being achieved by thermal radiation from the inner surface of the tube to the glass material.

The microwave equipment used in this experiment (also in other own previous experiments) was designed and made in Daily Sourcing & Research Company using a 800 W-microwave oven applied in the household for food preparation, constructively and functionally adapted for operation at high temperatures (above 1100 °C). The constructive and functional scheme of the oven (A) as well as the overall image of the equipment (B) are shown in Fig. 1.

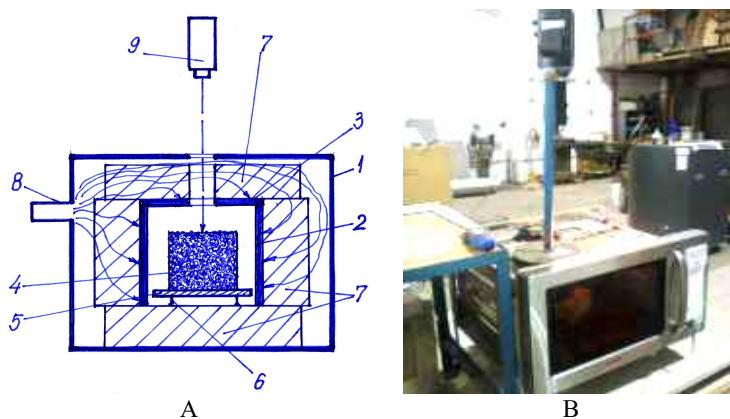


Fig. 1. Microwave equipment for preparing cellular glass

A – constructive and functional scheme: 1 – microwave oven; 2 – ceramic tube; 3 – ceramic lid; 4 – pressed sample; 5 – metal plate; 6 – support; 7 – ceramic protection; 8 – waveguide; 9 – radiation pyrometer; B – overall image of the equipment.

An important ability of potassium hydroxide (KOH) dissolved in water is the complete decomposition into ions of sodium (Na^+) and OH^- group. At the ambient temperature, the fine glass powder slowly reacts with the aqueous KOH solution. Silica (SiO_2) available in high ratios in the glass composition (over 70 % in the case of soda-lime-silica glass) reacts with hydrated KOH forming potassium silicate (K_2SiO_3) according to the following reaction:



By growing the process temperature to above 700 °C, the intensity of reaction (1) increases also. Upon reaching the glass transition temperature, the crystalline phase $\text{K}_2\text{CaSi}_2\text{O}_6 \cdot \text{H}_2\text{O}$ is formed, whose water of crystallization is released around 700 °C. Water vapour dissociates into oxygen and hydrogen, constituting the gases that contribute to the formation of bubbles in the softened mass of raw material, remaining blocked, to subsequently form cells.

It is known that the ability of melts containing silica to form glass is explained by the presence into these melts of three-dimensional silicon-oxygen polymeric structures, whose interaction leads to a significant growing of the melt viscosity upon cooling and the disorganization of the structure. Usually, the dissolution of SiO_2 particles in alkaline solutions involves the cleavage of siloxane bonds according to the equations (1) and (2) and the silica transfers in liquid phase in form of silicic acid ions with different levels of polymerization [19].



2.2 Materials

The materials that constituted the starting mix for preparing cellular glass were: post-consumer drinking bottle as raw material, sodium tetraborate decahydrate ($\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$) as a flux agent, and aqueous potassium hydroxide (KOH) solution as an expanding agent.

The post-consumer drinking bottle was composed of colourless glass (40 wt. %), green glass (30 wt. %), and amber glass (30 wt. %), with their chemical composition exhibited in Table 1. The recycled waste was cleaned of any possible contaminants, washed, broken in a crusher, ground in a ball mill, and sieved, the grain size being selected under 83 μm .

Table 1

Chemical composition of glass waste

Chemical composition	Colourless glass (%)	Green glass (%)	Amber glass (%)
SiO ₂	71.5	71.7	71.3
Al ₂ O ₃	2.1	1.8	2.0
CaO	12.1	11.9	12.0
Fe ₂ O ₃	0.1	-	0.2
MgO	1.1	1.2	1.0
Na ₂ O	13.3	13.1	13.0
K ₂ O	-	0.1	0.1
Cr ₂ O ₃	0.1	0.1	-
SO ₃	-	-	0.1

Sodium tetraborate decahydrate was chosen as a fluxing agent due to its high content of Na₂O, the best known chemical compound with flux properties, particularly for the glass industry. On the other hand, the boron from its composition plays an important role in growing the mechanical strength of cellular glass prepared with borax added.

An aqueous potassium hydroxide (KOH) solution was adopted as an expanding agent in this experiment. This choice has never been made until now. KOH is a strong alkali, very water-soluble, and highly corrosive. Other properties of KOH are: ability to degrade various materials, strong chemical base, high thermal stability, and reactivity toward acid. It is commercially available in flakes form, obtained by concentrating a purified electrolytic KOH solution [20].

2.3 Investigating methods to determine the cellular glass features

The apparent density was measured by the gravimetric method [21]. The porosity was calculated by the method of comparing the true and apparent density [22]. The thermal conductivity was measured by the guarded-comparative-longitudinal heat flow meter method (ASTM E1225-04) and the compressive strength was determined using a TA.XTplus Texture Analyzer (ASTM C552-17). The water absorption was determined based on the instructions provided in ASTM C240 standard and the microstructural configuration of the cellular glass samples was investigated with an ASONA 100X.

3. Results and discussion

3.1 Results

For the purpose of experimental production of high-porosity cellular glass made with a liquid blowing agent, four versions of the manufacturing recipe containing the

above-mentioned components were chosen. Table 2 indicates the values corresponding to each version.

Table 2

Composition of the experimental versions

Version	Coloured glass waste (%)	Sodium tetraborate hydroxide (%)	Aqueous KOH solution (%)
1	86.0	11.5	2.5
2	86.0	10.0	4.0
3	86.0	8.5	5.5
4	85.5	7.0	7.5

Physical-mechanical, heat, and morphological characteristics of samples corresponding to tried experimental versions are presented in Table 3.

Table 3

Physical-mechanical, heat, and morphological features

Feature	Version A	Version B	Version C	Version D
Apparent density ($\text{g}\cdot\text{cm}^{-3}$)	0.43	0.34	0.25	0.14
Porosity (%)	78.7	83.1	87.5	92.0
Heat conductivity ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$)	0.089	0.074	0.059	0.043
Compressive strength (MPa)	2.06	1.87	1.68	1.48
Water-absorbing (vol. %)	2.24	2.20	2.16	2.10
Cell size (mm)	0.1-0.3	0.1-0.4	0.3-0.6	0.7-0.9

Results of the main characteristics of cellular glass specimens presented in Table 3 show the decreasing values of apparent density (from 0.43 to 0.14 $\text{g}\cdot\text{cm}^{-3}$) with growing the aqueous KOH solution used in the experiment (from 2.5 to 7.5 %). Also, heat conductivity registered a significant reduction (from 0.089 to 0.043 $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$). The high porosity of cellular glass samples influenced the relatively low level of compressive strength, whose values were in the range of 1.48-2.06 MPa, without being an obstacle to applications in the field of thermal insulation in construction. The water absorption measured in the case of the four cellular glass samples was within normal limits for this material type, i. e. between 2.10-2.24 vol. %.

The appearance of the outer surface of the four cellular glass samples is exhibited in Fig. 2.

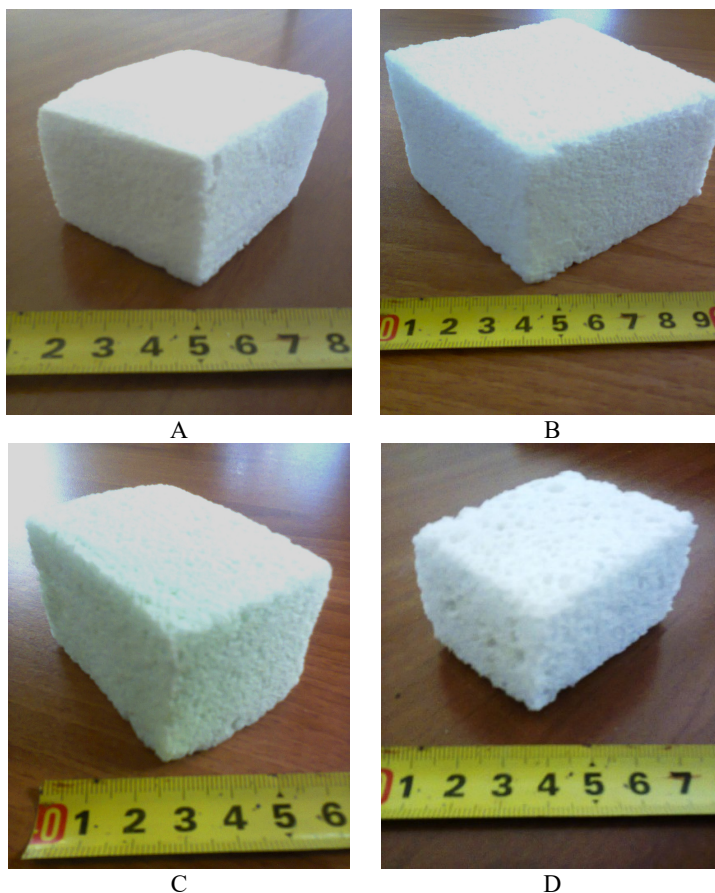
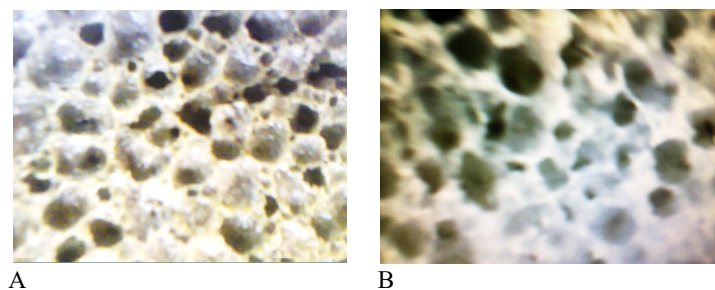


Fig. 2. Appearance of outer surface of cellular glass samples
A – version 1; B – version 2; C – version 3; D – version 4.

The obvious increase of sample porosity obtained by growing the proportion of KOH solution is observable in images shown in Fig. 2. Sample D prepared by using the highest content of KOH solution is characterized by closed cells with dimensions up to about 1 mm. The analysis of the microstructural structures of the samples was performed based on the pictures in Fig. 3.



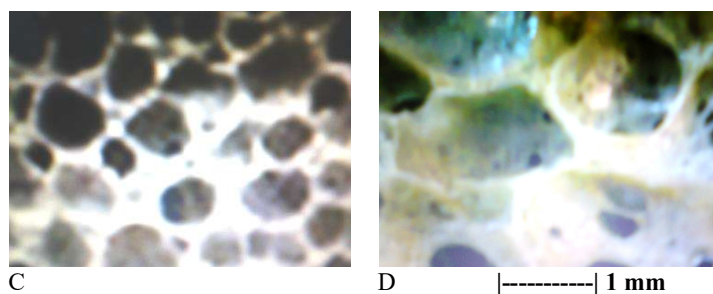


Fig. 3. Microstructural aspect of high-porosity cellular glass samples
A – version 1; B – version 2; C – version 3; D – version 4.

The cell size ranges were determined for each of the four samples, the results being included in Table 3. Sample A had the lowest cell sizes in the range of 0.1-0.3 mm, while sample B had values between 0.1-0.4 mm. Sample C was characterized by higher cell dimensions within the limits of 0.3-0.6 mm, while sample D reached the highest size range (0.7-0.9 mm).

3.2 Discussion

The use of aqueous KOH solution as an expanding agent is a technological novelty promoted and tested by the authors' team in the manufacturing process of high-porosity cellular glass. Also, a fluxing agent from the borax category, namely sodium tetraborate decahydrate, was adopted in association with the mentioned expanding agent. In general, this material type is frequently used, especially in the glass industry being considered one of the most important fluxing agents due to its high Na_2O content.

According to the literature data [14, 17], the aqueous solution of NaOH as a foaming agent together with borax and soda-lime-silica residual glass is a recently used version. By varying the borax/foaming agent ratio, different values of the density of cellular glass were obtained (between $0.16\text{--}0.79\text{ g}\cdot\text{cm}^{-3}$), the porosity reaching extremely high values (up to 92 %). Increasing the content of $\text{NaOH}\cdot\text{H}_2\text{O}$ solution contributed to the decrease of the density value and reducing the open porosity proportion. In contrast, borax favoured growing the cellular glass density and the generation of a closed-cell structure.

By comparison, cellular glass produced with KOH solution allowed lower values of apparent density (up to $0.14\text{ g}\cdot\text{cm}^{-3}$) and heat conductivity (up to $0.043\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$).

The application of electromagnetic waves as energy carriers, whose power is converted into heat through direct contact with the material to be heated, has proven to be a very fast heating procedure and at the same time very cost-effective in terms of energy. The paper [23] noted these energy performances of microwaves for glass processing compared to conventional processes (such as glass melting, sintering, devitrification, coating, reinforcing, etc.). However, commercial glass powder (soda-

lime-silica glass type) subjected to direct microwave heating in 20 L-useful volume oven powered by 800 W suffered serious damage of its internal structure by heating to sintering/foaming temperatures of 850-950 °C [24], according to experimental observations of the current paper authors. The optimal resolving adopted by the authors was the own technical solution to temper the intensity effect of direct contact of the microwave flux with the glassy material by placing a microwave-absorbing protective screen between the wave emitting source and the heated material.

4. Conclusions

The work objective was to manufacture a cellular glass with excellent thermal insulation properties under the conditions of applying the unconventional microwave heating technique of the glass-based mixture. The originality of this technique applying consisted in choosing the own solution of mixed heating, preponderantly direct and partially indirect, by placing a microwave-absorbing protective screen between the wave emission source and the pressed material mixture. Another originality of the work in technological terms was the choice of aqueous KOH solution as a foaming agent instead of the NaOH solution successfully tried in previous recent experiments. The results were qualitatively similar, while the microwave applying led to energy advantages.

References

- [1]*** „EU Packaging Waste Generation with Record Increase”, Eurostat, 2023. <https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20231019-1>
- [2]*** „Packaging Waste Statistics”, Eurostat Statistics Explained, 2021. https://ec.europa.eu/eurostat/statisticsexplained/index.php?title=Packaging_waste_statistics&oldid=542594A
- [3] *** „The Dark Side of Glass Recycling: Unveiling the Disadvantage”, Guangzhou SUIBO, Jiangnan, Nancun Town, China, 2025. <https://www.suibosorting.com/glass-sorting-machine/the-dark-side-of-glass-recycling-unveiling-the-disadvantages>
- [4]G. Scarinci, G. Brusatin, E. Bernardo, „Glass Foams”, in Cellular Ceramics: Structure, Manufacturing, Properties and Applications, M. Scheffler, P. Colombo (Eds.), Wiley-VCH Verlag GmbH & Co KGaA, Weinheim, Germany, 2005, pp. 158-176, <https://doi.org/10.1002/3527606696>
- [5] L. Paunescu, S.M. Axinte, M.F. Dragoescu, B.V. Paunescu, „Effective microwave heating method for manufacturing glass foam from glass waste”, Revista Romana de Inginerie Civila, Matrix Rom Publisher, Bucharest, vol. 12, no. 4, 2021, pp. 482-491.
- [6] A.V. Lunip, S. Kanagesan, S.A.B. Aziz, B.P. Chandra Rao, „Physical Properties of Foam Glass Ceramics Prepared by Cathode Ray Tube Panel Glass and Clam Shell”, in International Journal of Science, Engineering and Technology Research, vol. 5, no. 7, 2016, pp. 2344-2352.
- [7] A. Zhai, Z. Li, Y. Zhu, J. Zhang, X. Wang, L. Zhao, L. Pan, P. Wang, „Effect of Sb₂O₃ on the Mechanical Properties of the Borosilicate Foam Glasses Sintered at Low Temperature”, in Advances in Materials Science and Engineering, vol. 2014, no. 2, 2014, pp. 1-6.
- [8] A.V. Gorokhovskiy, J.I. Escalante Garcia, J. Mendez-Nonell, V.A. Gorokhovskiy, D.V. Mescheryakov, „Foamed Glass-Ceramic Materials Based on Oil Shale By-Products”, in Glass Science and Technology, vol. 75, 2002, pp. 259-262.

- [9] E. Fidancevska, B. Mangutova, M. Milosevski, J. Bassert, „Obtaining of Dense and Highly Porous Materials from Metallurgical Slag”, in *Science of Sintering*, vol. 35, no. 2, 2003, pp. 85-91. <https://doi.org/10.2298/SOS0302085F>
- [10] M. Pelino, „Recycling of Zinc-Hydrometallurgy Wastes in Glass and Glass Ceramic Materials”, in *Waste Management*, vol. 20, 2000, pp. 561-568.
- [11] Z. Li, Z. Luo, X. Li, T. Liu, L. Guan, T. Wu, A. Lu, „Preparation and Characterization of Glass Ceramic Foams with Quartz Sand and Coal Gangue”, in *Journal of Porous Materials*, vol. 23, 2016, pp. 231-238.
- [12] P. Chakartnarodom, P. Ineure, „Foam Glass Development Using Glass Cullet and Fly Ash or Rice Husk Ash as the Raw Materials”, in *Key Engineering Materials*, vol. 608, 2014, pp. 73-78. <https://doi.org/10.4028/www.scientific.net/KEM.608.73>
- [13] Sabrina Arcaro, B. Goulart de Oliveira, M. Tramontin Souza, F.R. Cesconeto, L. Granados, A.P. Novaes de Oliveira, „Thermal Insulating Foams Produced from Glass Waste and Banana Leaves”, in *Material Research*, vol. 19, no. 5, 2016, pp. 1064-1069. Editura Științifică și Enciclopedică, București, 1980.
- [14] L.L. da Silva, L.C. Nunes Ribeiro, G. Santacruz, S. Arcaro, A. Koop Alves, C. Pérez Bergmann, „Glass Foams Produced from Glass and Yerba Mate (*Ilex Paraguariensis*)”, in *FME Transactions*, vol. 46, no. 1, 2017. <https://doi.org/10.5937/fmet1801070L>
- [15] Fernanda Andreola, L. Barbieri, I. Lancellotti, H.R. Fernandes M.J. Pascual, J.M.F. Ferreira, „The Use of Egg Shells to Produce Cathode Ray Tube (CRT) Glass Foams”, in *Ceramics International*, Elsevier, vol. 39, 2013, pp. 9071-9078. <https://doi.org/10.1016/j.ceramint.2013.05.002>
- [16] Y. Attila, M. Güden, A. Tasdemirci, „Foam Glass Processing Using a Polishing Glass Powder Residue”, in *Ceramics International*, Elsevier, vol. 39, no. 5, 2013, pp. 5869-5877. <https://doi.org/10.1016/j.ceramint.2012.12.104>
- [17] J. Foreman, „Doing Double Duty in the Circular Economy-Creating Foam Glass from Waste Materials”, in *Journal of the American Ceramic Society*, ACS Publications, Washington D.C., the United States, 2020. <https://ceramics.org/ceramic-tech-today/environment/doing-double-duty-in-the-circular-economy-creating-foam-waste-materials>
- [18] L. Paunescu, M.F. Dragoescu, S.M. Axinte, F. Cosmulescu, B.V. Paunescu, „Conversion into Heat of Microwave Power Used in the Manufacturing Process of Glass Foam”, in *Nonconventional Technologies Review*, "Politehnica" Publishing House, Timisoara, Romania, vol. 25, no. 1, 2021, pp. 21-28.
- [19] A.S. Brykov, „Glass Formation and Gelation in the System $K_2O-SiO_2-H_2O$ ”, in *Russian Journal of Applied Chemistry*, vol. 79, no. 4, 2006, pp. 529-533. <https://doi.org/10.1134/S1070427206040045>
- [20] *** „Uses for KOH in Soap, Energy & Batteries, Manufacturing, and More”, AG Chemi Group, Rakovník, Czech Republic, 2021. <https://blog.agchemigroup.eu/uses-for-koh-in-soap-energy-batteries-manufacturing-and-more>
- [21] *** *Manual of Weighing Applications, Part 1, Density*, 1999. http://www.docplayer.net/21731890-Manual-of-weighing-applications-part-1-density_html
- [22] L.M. Anovitz, D.R. Cole, „Characterization and Analysis of Porosity and Pore Structures”, in *Reviews in Mineralogy and Chemistry*, vol. 80, no. 1, 2005, pp. 61-164. <https://doi.org/10.2138/rmg.2015.80.04>
- [23] Oxana V. Kharissova, B.I. Kharissov, J.J. Ruiz Valdés, „Review: The Use of Microwave Irradiation in the Processing of Glasses and their Composites” in *Industrial & Engineering Chemistry Research*, ACS Publications, vol. 49, no. 4, 2010, pp. 1457-1466. <https://pubs.acs.org/doi/10.1021/ie9014765>
- [24] L. Paunescu, S.M. Axinte, B.T. Grigoras, M.F. Dragoescu, A. Fiti, „Testing the Use of Microwave Energy to Produce Foam Glass”, in *European Journal of Engineering and Technology*, Progressive Academic Publishing, vol. 5, no. 4, 2017, pp. 8-17, ISSN: 2056-5860.

Thermal analysis of electrical cables buried in the ground

Analiza termică a cablurilor electrice îngropate în sol

Sorin DIMITRIU¹, Dragoș PAVEL²

¹National University of Science and Technology „Politehnica” Bucharest, Faculty of Mechanical Engineering and Mechatronics
Splaiul Independenței 313, sector 6, Bucharest, Romania
E-mail: dimitriu47@yahoo.com

²Police Academy „Alexandru Ioan Cuza”, Bucharest, Faculty of Firefighters
Șoseaua Morarilor 3, sector 2, Bucharest, Romania
E-mail: pavel_dragos@yahoo.co.uk

DOI: 10.37789/rjce.2026.17.3.7

Abstract. *The paper proposes a calculation model for the temperature of electrical cables buried in the ground, in protective tubes. The heat transfer between the cable and the ground is analysed similarly to the heat propagation mode through cooling fins. The cable insulation and the protective tube are unrolled in the form of flat blades and the temperature distribution in the tube, the temperature of the contact area and the temperature of the electrical conductor are determined. For a given cable, the coincidence of the results with those in the manufacturer's catalogue confirms the validity of the model.*

Key words: *buried cables, heating of electrical conductors, fire risk in buried cables*

Rezumat. *Lucrarea propune un model de calcul pentru temperatura cablurilor electrice îngropate în pământ, în tuburi de protecție. Transferul de căldură dintre cablu și pământ este analizat similar modului de propagare a căldurii prin aripioarele de răcire. Izolația cablului și tubul de protecție sunt derulate sub formă de lamele plate și se stabilește distribuția temperaturii în tub, temperatura zonei de contact și temperatura conductorului electric. Pentru un anumit cablu, coincidența rezultatelor cu cele din catalogul producătorului confirmă validitatea modelului.*

Cuvinte cheie: *cabluri îngropate, încălzire conductori electrice, risc de incendiu la cabluri îngropate*

1. Introduction.

In modern urban infrastructures, the electric power distribution cables suspended on poles have disappeared, the entire distribution network being made by buried cables, both directly in the ground and in cable ducts. Given the constantly increasing energy density and the increasingly limited laying space, fires that can occur in this underground network pose a major technical risk. Unlike fires that start on the surface,

underground fires evolve in a closed environment, with non-existent or very low ventilation, producing an accumulation of heat, gases and pressure that can lead to tragic events. The initiation of such events is determined by excessive heating of the cables, the occurrence of short circuits generated by insulation defects, overload, high thermal resistivity of the soil and unfavourable heat dissipation conditions. The main element that determines the risk of fire and the lifespan in these conditions is the temperature that the electric cable reaches during operation [1], [2].

A number of factors can be distinguished that determine the operating temperature of a buried electrical cable and the temperature field that forms around it.

Thermal overload, generated by exceeding the current value above the nominal capacity of the cable (ampacity), is a first critical mechanism. Heat generation, produced by the dissipation of electrical energy in the cable through the Joule-Lenz effect, is proportional to the square of the operating current, which means that a relatively small increase in its current produces a significant increase in the temperature of the conductor. The insulation of modern electrical cables buried in the ground is mainly made of polymeric materials, chosen for their resistance to humidity, temperature, chemicals and mechanical stress. Exceeding the maximum permissible temperature accelerates the degradation of the polymeric insulation, reducing its dielectric strength and increasing the probability of an electric arc [3].

The thermal resistivity of the soil, which can vary depending on humidity, composition and compaction, can amplify the thermal degradation process of the insulation. Dry or sandy soils have a low thermal conductivity, which reduces their ability to absorb the heat generated by the cable [4].

Insulation failure is another important factor, which can occur through thermal aging, mechanical damage or water infiltration. Aged and weakened insulation can lead to the appearance of an electric arc, a phenomenon characterized by local temperatures of over 3000°C, sufficient condition to ignite combustible materials around the cable. In underground spaces, where cables are often grouped and placed next to each other, an electric arc can trigger a chain fire, simultaneously affecting several circuits. According to analyses carried out by IEEE and CIGRÉ, electric arcs are one of the main causes of fires in underground distribution networks [5].

Insufficient ventilation is another critical element. Cables laid in cable ducts, galleries or ducts are in a closed environment, where air cannot efficiently evacuate heat. In this way, the ambient temperature gradually increases, reducing the temperature difference required for heat transfer and leading to a dangerous accumulation of heat in the mass of the cable and insulation. In addition, insulating materials such as PVC, XLPE or synthetic rubber are combustible and, once ignited, can sustain combustion and produce dense smoke and toxic gases, including hydrogen chloride (HCl) which in humid conditions forms hydrochloric acid, carbon monoxide (CO) and aromatic hydrocarbons [6].

Accumulation of flammable gases in underground spaces. Pyrolysis of the plastic materials from which cable insulation is made produces combustible gases which, in the absence of ventilation, can form explosive mixtures. In such conditions, a spark or an

electric arc can trigger a deflagration. Numerous technical reports on fires in underground urban networks show that explosions in electrical conduits are frequently associated with the accumulation of gases resulting from the thermal degradation of cables [7]. In addition, due to the thermal regime determined by the accumulation of heat, polyethylene (PE) natural gas distribution pipes laid in proximity can also be affected, a situation in which their accumulation through infiltration can lead to disasters.

The prevention of underground fires caused by buried electrical cables requires an integrated approach, including both design measures and appropriate operation and maintenance. In the design phase, it is essential to correctly dimension the cables according to the IEC 60287 and IEC 60853 standards, which provide calculation methods for the allowable current depending on the thermal conditions of the soil. The use of filling materials with high thermal conductivity (thermal backfill) can significantly reduce the cable temperature, as shown in studies in the specialized literature [8]. Also, avoiding excessive grouping of cables, protecting them and ensuring routes with adequate thermal dissipation are fundamental measures. In operation, monitoring the temperature of cables through distributed sensors (DTS – Distributed Temperature Sensing) allows early detection of areas with high thermal risk. As maintenance, periodic inspections, including thermal imaging at the cable ends and checking connections, can prevent contact defects that generate hot spots. In addition, the use of cables with flame retardant insulation and LSZH (Low Smoke Zero Halogen) sheaths reduces the risk of fire propagation and smoke toxicity.

Underground fires due to heating of electrical cables are the result of a complex combination of thermal, electrical and infrastructure factors. They can be prevented by rigorous design, responsible operation and continuous maintenance. In the context of increasing energy demand and densification of urban networks, understanding the heating mechanisms of underground cables and associated risks, becomes essential for the protection of critical infrastructures and public safety. Consequently, the problem of studying the development of the phenomenon of heating of underground electrical cables, the accumulation of heat and its propagation in the environment surrounding buried cables, constitutes a topic of study that is not only interesting, but also very useful in preventing events with particularly serious consequences, both for the infrastructure and for its users [9, 10, 11, 12].

This paper proposes a calculation method by which the temperature of an electrical cable laid inside a protective tube buried in the ground can be determined, depending on the operating conditions.

2. Mathematic model.

The mathematical model assumes that the heat transfer in the cable insulation and in the wall of the protective tube is similar to the heat transfer through the rectangular cooling fins. For the construction of this model, it was considered that half of the circumference of the insulation and the protective tube, respectively, is deployed in the

form of rectangular cooling fins that receive heat from the conductor material and release it to the ground.

2.1. Physical model.

The physical model is presented in Figure 1. The electric cable having the section corresponding to the diameter d and the insulation thickness δ_{is} is considered to be inserted inside a protective tube with diameter D and wall thickness δ_t . The cable insulation and the wall of the protective tube are in direct contact over a length of the circumference corresponding to the contact angle θ . The tube is considered to be buried in the soil having a constant temperature t_s . The geometry of the system is considered to be symmetrical with respect to the vertical diameter $A-A$. During operation the cable heats up due to dissipation by the Joule-Lenz effect, generating a heat flux:

$$\dot{Q} = RI^2 \text{ [W/m]} \quad (1)$$

where R [Ω/m] is the specific resistance of the cable, and I [A] is the electric current flowing through the cable. The air in the space between the cable and the protective tube, having a very low thermal conductivity coefficient and being at the same time an unventilated environment, behaves as a thermal insulator, so that the heat transfer between the cable and the protective tube is carried out only through the contact spot whose width is determined by the contact angle θ [rad]. The heat then propagates by conduction through the wall of the protective tube to the soil with which it is in direct contact on its outer surface.

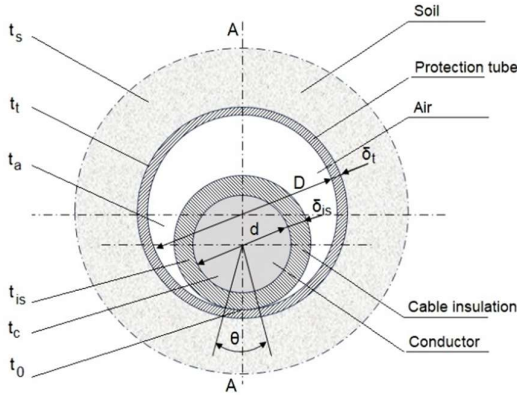


Fig. 1. Physical model

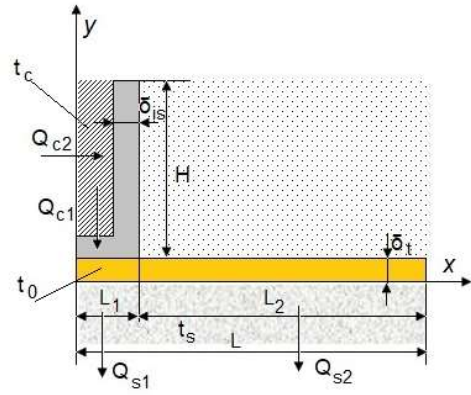


Fig. 2. The calculation model

To build the mathematical model, considering the symmetry with respect to the $A-A$ axis, only half of the system formed by the protective tube and the cable inside it was considered. The wall of the tube, corresponding to the length L of the semicircle $A-A$ was deployed horizontally (x -axis), and the arc of a circle with the length H , corresponding to the cable insulation starting from the contact spot boundary, was deployed vertically (y -axis). The direct contact was considered on the length L_1 , corresponding to the contact semi angle $\theta/2$. In this way, the system shown in Figure 2

was obtained, equivalent in terms of heat transfer to the real one and whose dimensions are:

$$L = \frac{\pi}{2}D; L_1 = \frac{\theta}{4}(d+2\delta_{is}); L_2 = L - L_1; H = \frac{\pi}{2}(d+2\delta_{is}) - L_1 \quad (1)$$

The heat flux produced in the electrical conductor is transmitted to the direct contact area, in the form of flux $\dot{Q}_{c1}$ and by conduction in the insulation in the form of flux $\dot{Q}_{c2}$. To the ground, the heat is transmitted in the area of the direct contact spot, in the form of flux $\dot{Q}_{s1}$ and by conduction along the wall of the protective tube in the form of flux $\dot{Q}_{s2}$, the energy balance having the form:

$$\dot{Q} = RI^2 = 2(\dot{Q}_{c1} + \dot{Q}_{c2}) = 2(\dot{Q}_{s1} + \dot{Q}_{s2}) \text{ [W/m]} \quad (3)$$

2.2. Heat transfer through the tube wall.

The heat exchange with the ground is carried out only on the outer surface of the tube, along the length L_2 , the other surface in contact with the air inside being considered thermally insulated. It is considered that from the contact spot area having temperature t_0 , the heat is transmitted by conduction through the tube wall and from there to the ground having temperature t_s , through a layer having thickness $\delta_s = D/2$. For an elementary section of thickness dx and width of 1m, in which the temperature is t (Figure 3), the energy balance has the expression:

$$\dot{Q}_s = \dot{Q}_{x+dx} - \dot{Q}_x \quad (4)$$

where:

$$\dot{Q}_x = -\lambda_t \frac{dt}{dx} \delta_t; \dot{Q}_{x+dx} = \dot{Q}_x + \lambda_t \frac{d^2t}{dx^2} \delta_t dx; \dot{Q}_s = k_s(t - t_s)dx \quad (5)$$

λ_t [W/mK] being the thermal conductivity coefficient of the protective tube material, and k_s the heat transfer coefficient in the soil:

$$k_s = \frac{1}{R_{ts}} = \frac{\lambda_s}{\delta_s} \text{ [W/m}^2\text{K]} \quad (6)$$

In relation (6) λ_s [W/mK] is the thermal conductivity coefficient of the soil, and δ_s [m] is the thickness of the layer through which heat propagates in the soil to the area with temperature t_s .

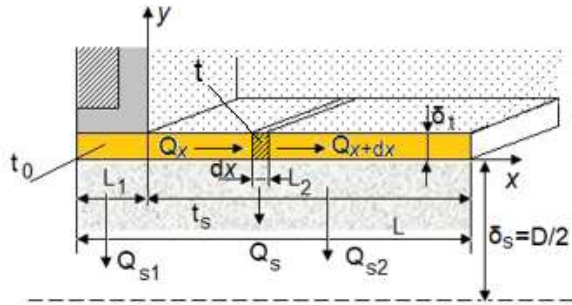


Fig. 3. Heat transfer model between the protection tube and the ground.

From relations (4) and (5) we obtain the differential equation:

$$\frac{d^2 \theta_t}{dx_2^2} = m_t^2 \theta_t; m_t = \sqrt{\frac{k_s}{\lambda_t \delta_t}}; \theta_t = t - t_s \quad (7)$$

The solution to equation (7) has the form:

$$\theta_t(x) = C_1 e^{m_t x} + C_2 e^{-m_t x} \quad (8)$$

with boundary conditions:

$$x = 0 \rightarrow \theta_t = \theta_{t0} = t_0 - t_s; x = L_2 \rightarrow \frac{dt}{dx} = 0 \text{ (zero heat flux)} \quad (9)$$

The expression for the temperature field in the tube wall results in the form:

$$t(x) = t_s + (t_0 - t_s) \frac{\cosh m_t (L_2 - x)}{\cosh m_t L_2} \text{ [}^\circ\text{C]} \quad (10)$$

To determine the temperature in the contact spot area, it is considered that the unfolded tube portion behaves like a flat fin. As a result, the heat flux given off to the ground through the portion of length L_2 has the expression:

$$\dot{Q}_{s2} = k_s \eta_t L_2 (t_0 - t_s) \text{ [W/m]} \quad (11)$$

where η_t is the efficiency of the fin equivalent to the arc of the tube wall:

$$\eta_t = \frac{\tanh m_t L_2}{m_t L_2} \quad (12)$$

The heat flux transmitted to the ground by the contact area with temperature t_0 has the expression:

$$\dot{Q}_{s1} = k_s L_1 (t_0 - t_s) \text{ [W/m]} \quad (13)$$

and as a result, the total heat flux given off to the ground on the perimeter of the protective tube can be written:

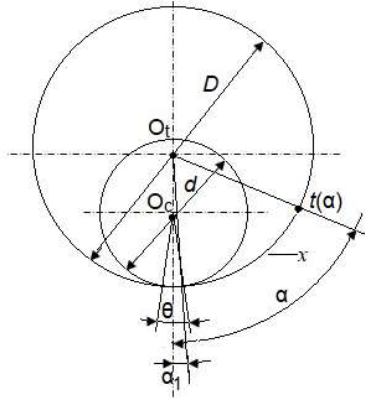


Fig.4. Positioning the point with temperature $t(\alpha)$ on the tube circumference.

$$\dot{Q}_s = 2 (\dot{Q}_{s1} + \dot{Q}_{s2}) = 2k_s(L_1 + \eta_t L_2)(t_0 - t_s) = R I^2 \quad [W/m] \quad (14)$$

where the temperature of the contact area results from:

$$t_0 = t_s + \frac{R I^2}{2k_s(L_1 + \eta_t L_2)} \quad [^\circ\text{C}] \quad (15)$$

The temperature at any point on the circumference of the protective tube, given by relation (11), can be expressed as a function of the angle α [rad] at the centre O_t of the tube (Figure 4):

$$t(\alpha) = t_0 \quad [^\circ\text{C}] \quad \left(\alpha \leq \theta \frac{d}{2D} \right)$$

$$t(\alpha) = t_s + (t_0 - t_s) \frac{\cosh m_t \frac{D}{2} (\pi - \alpha)}{\cosh m_t L_2} \quad [^\circ\text{C}] \quad \left(\alpha > \theta \frac{d}{2D} \right) \quad (16)$$

2.3. Heat transfer in cable insulation.

The heat exchange between the conductor and the insulation is carried out on the inner face, along the length H , the other face in contact with the air inside being considered thermally insulated. It is considered that the heat transfer takes place through the insulation, up to the contact surface area, having the temperature t_0 from where it continues to the wall of the protective tube and then into the ground. For an elementary section of thickness dy and width of 1m, in which the temperature is t (Figure 5), the energy balance has the expression:

$$\dot{Q}_c = \dot{Q}_{y+dy} - \dot{Q}_y \quad (17)$$

where:

$$\dot{Q}_y = -\lambda_{is} \frac{dt}{dy} \delta_{is}; \quad \dot{Q}_{y+dy} = \dot{Q}_y - \lambda_{is} \frac{d^2 t}{dy^2} \delta_{is} dy; \quad \dot{Q}_c = k_c (t_c - t) dy \quad (18)$$

λ_{is} [W/mK] being the thermal conductivity coefficient of the insulation material, and k_c the thermal transfer coefficient in the conductor:

$$k_c = \frac{I}{R_{tc}} = \frac{2\lambda_c}{d} \quad [W/m^2K] \quad (19)$$

In relation (19) λ_c [W/mK] is the thermal conductivity coefficient of the conductor material, and d [m] is the diameter of the conductor cross-section.

From relations (17) and (18) the differential equation is obtained:

$$\frac{d^2 \theta_c}{dy^2} = m_c^2 \theta_c; \quad m_c = \sqrt{\frac{k_c}{\lambda_{is} \delta_{is}}}; \quad \theta_c = t_c - t \quad (20)$$

The solution to equation (20) has the form:

$$\theta_c(y) = C_1 e^{m_c y} + C_2 e^{-m_c y} \quad (21)$$

with the boundary conditions:

$$y=0 \rightarrow \theta_c = \theta_{c0} = t_c - t_0; \quad x=H \rightarrow \frac{dt}{dy} = 0 \text{ (zero heat flux)} \quad (22)$$

The expression of the temperature field in the tube wall results in the form:

$$t(y) = t_c + (t_c - t_0) \frac{\cosh m_c(H - y)}{\cosh m_c H} \text{ [}^\circ\text{C]} \quad (23)$$

To determine the temperature in the conductor, it is considered that the unfolded insulation portion behaves like a flat fin. As a result, the heat flux transferred by the conductor through the portion of length H has the expression:

$$\dot{Q}_{s2} = k_c \eta_c H (t_c - t_0) \text{ [W/m]} \quad (24)$$

where η_c is the efficiency of the fin equivalent to the arc of the insulation:

$$\eta_c = \frac{\tanh m_c H}{m_c H} \quad (25)$$

The heat flux transmitted to the protection tube through the contact area with temperature t_0 has the expression:

$$\dot{Q}_{c1} = k_c L_1 (t_c - t_0) \text{ [W/m]} \quad (26)$$

and as a result, the total heat flux given off by the conductor through the insulation on its perimeter can be written in the form:

$$\dot{Q}_c = 2(\dot{Q}_{c1} + \dot{Q}_{c2}) = 2k_c(L_1 + \eta_c L_H)(t_c - t_0) = RI^2 \text{ [W/m]} \quad (27)$$

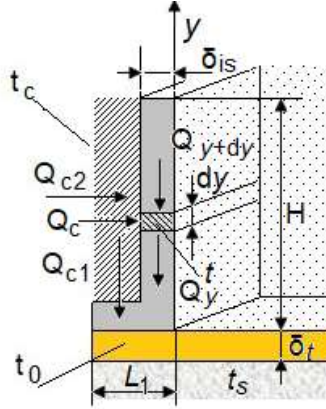


Fig.5. Heat transfer model between conductor and insulation.

where does the conductor temperature come from:

$$t_c = t_0 + \frac{RI^2}{2k_c(L_1 + \eta_c H)} \text{ [}^\circ\text{C]} \quad (28)$$

Relations (15) and (28) can be combined in the form:

$$t_c = t_s + \frac{RI^2}{2} \left[\frac{1}{k_s(L_l + \eta_t L_2)} + \frac{1}{k_c(L_l + \eta_c H)} \right] [^{\circ}\text{C}] \quad (29)$$

from which the expression for the thermal resistance between the conductor and the ground results:

$$R_{tcs} = \frac{I}{2} \left[\frac{1}{k_s(L_l + \eta_t L_2)} + \frac{1}{k_c(L_l + \eta_c H)} \right] [\text{mK/W}] \quad (30)$$

3. Results and discussions

For testing the model, a medium voltage cable with cross-linked polyethylene (XLPE) insulation and PVC sheath was considered, for the nominal voltage of 12/20 kV, type NA2XSY, from the production of IPROEB Bistrița [13]. The cable is intended for the distribution of electrical energy in fixed installations, indoors, outdoors and buried. The cable consists of a compacted aluminium multi-wire conductor, insulated with XLPE, with a copper wire and tape screen and an outer PVC sheath. The cable structure is shown in Figure 6.

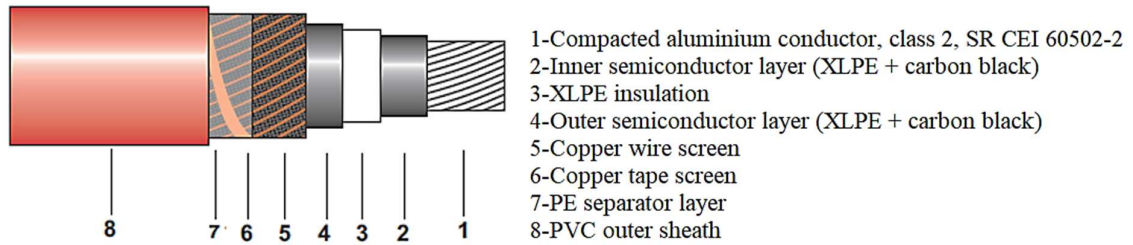


Fig. 6. The structural elements of the MT NA2XSY 12/20kV cable [13].

The cable is manufactured in nine sizes, differentiated by the cross-sectional area of the multi-wire aluminium conductor. Table 1 presents the construction dimensions for the nine cable sizes.

Table 1

Dimensions of MV NA2XSY 12/20 kV cables [13].

Conduct. / Screen section [mm ²]	Conduct. outer diameter [mm]	Semicond. inn. layer thickness [mm]	XLPE insulation thickness [mm]	Semicond. out. layer thickness [mm]	Copper screen thickness [mm]	Separator layer thickness [mm]	Outer sheath thickness [mm]	Cable outer diameter [mm]	Specific electrical resistance [Ω/km]
1x35/16	6,86	0,5	5,5	0,5	0,25	1,5	2,5	28,37	0,806
1x50/16	8,20	0,5	5,5	0,5	0,24	1,5	2,5	29,67	0,564
1x70/16	9,70	0,5	5,5	0,5	0,22	1,5	2,5	31,14	0,403
1x95/16	11,30	0,5	5,5	0,5	0,21	1,5	2,5	32,72	0,297
1x120/16	12,70	0,5	5,5	0,5	0,20	1,5	2,5	34,09	0,235
1x150/16	14,20	0,5	5,5	0,5	0,19	1,5	2,5	35,68	0,188
1x150/25	14,20	0,5	5,5	0,5	0,29	1,5	2,5	35,78	0,188
1x185/25	15,77	0,5	5,5	0,5	0,27	1,5	2,5	37,32	0,152
1x240/25	17,96	0,5	5,5	0,5	0,25	1,5	2,5	39,47	0,118
1x300/25	20,08	0,5	5,5	0,5	0,24	1,5	2,5	41,56	0,094

In order to apply the mathematical model, the cable insulation was considered homogeneous, having the real thickness and an equivalent thermal conductivity coefficient, according to the structure and materials of the n layers that make up the insulation (Table 2):

$$\lambda_{ec} = \frac{\ln \frac{d_{n+1}}{d_1}}{\sum_{i=1}^n \left(\frac{1}{\lambda_i} \ln \frac{d_{i+1}}{d_i} \right)} \quad [\text{W/mK}] \quad (31)$$

Table 2

Thermal characteristics of cables.

Cable Type	1x35/16	1x50/16	1x70/16	1x95/16	1x120/16	1x150/25	1x185/25	1x240/25	1x300/25
R_t [mK/W]	0,714	0,654	0,599	0,551	0,516	0,481	0,451	0,416	0,387
λ_{ec} [W/mK]	0,316	0,313	0,310	0,307	0,305	0,306	0,304	0,301	0,299
δ_{is} [mm]	10,75	10,74	10,72	10,71	10,70	10,79	10,77	10,75	10,74

Since the space between the conductor and the protective tube is not ventilated, the air in this space behaves as a thermal insulator and as a result the heat transfer between the conductor and the protective tube is carried out only on the direct contact area. Due to the low conductivity coefficient of the protective tube material ($\lambda_{PVC} = 0.17 \text{ W/mK}$), the heat transfer to the ground through the protective tube wall is noticeable only on an arc of a circle of $20^\circ \dots 30^\circ$ on both sides, around the contact area. Figure 7 shows the temperature distribution in the protective tube wall, according to relations (16), (17) and (18), for the cable with a cross section of 150 mm^2 for different values of the working current.

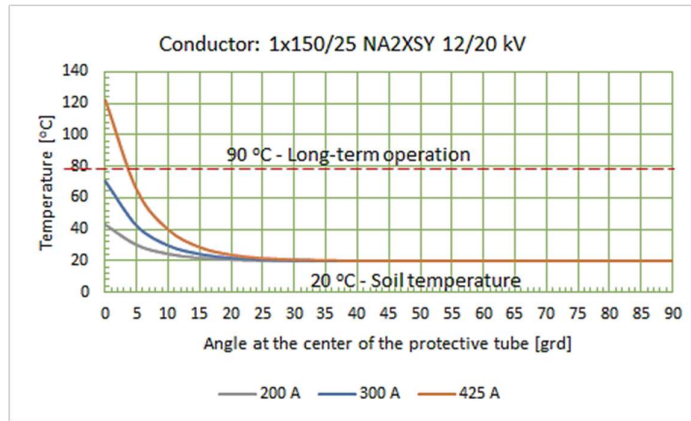


Fig. 7. Temperature variation in the wall of the PVC protective tube

According to the manufacturer's catalogue data [13], the maximum current for this cable, in long-term operation, is about 350 A, a value at which the cable reaches the maximum operating temperature of 90°C , up to which insulation damage does not occur. It can be seen that the dangerous zone where insulation damage and its penetration can occur is in the contact zone. As long as the current is below the limit

value, the temperature in this zone does not affect the insulation, exceeding it leading to the local formation of a high-temperature zone that can melt the insulation.

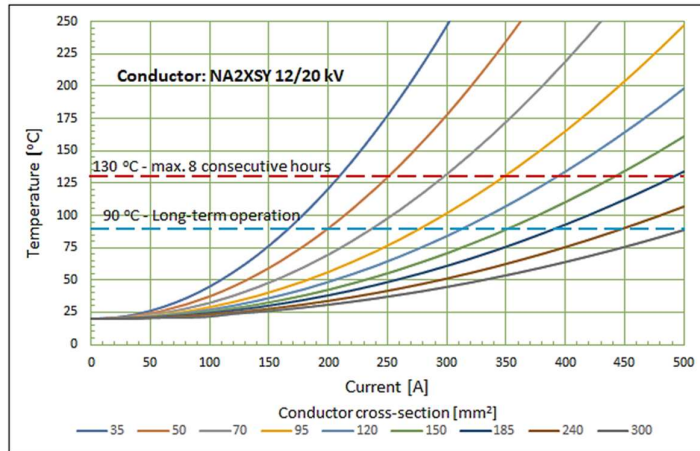


Fig. 8. Temperature variation depending on current and cross section.

The maximum current at which the limit temperature is reached in the conductor at which insulation damage begins depends on the conductor cross-section. Figure 8 shows the variation of the conductor temperature in relation to the value of the operating current, for the series of nine values of the cross-section of the MV conductor, NA2XSY 12/20kV calculated according to the model developed in the work.

The manufacturer guarantees safe operation at higher temperatures, up to 130 °C, provided that they are not exceeded for more than 8 consecutive hours and not more than 125 hours per year [13]. Figure 9 shows the maximum permissible current values for continuous load operation at a temperature of 90 °C for different installation situations for the NA2XSY 12/20 kV cable, according to the manufacturer's catalogue.

The calculation results are compared with these data.

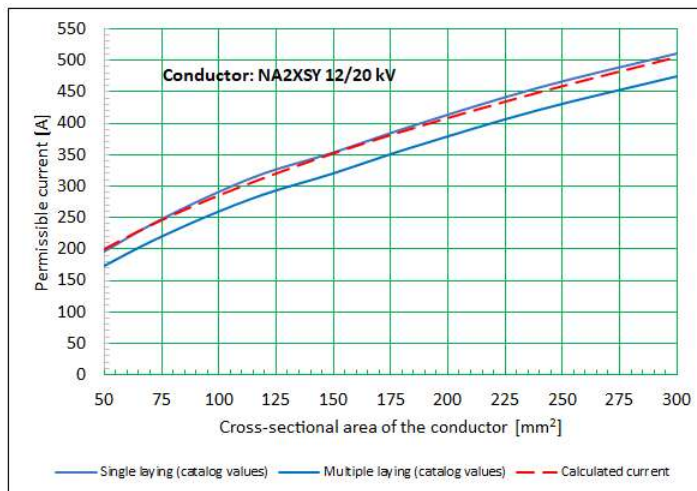


Fig.9. The allowable current at the temperature of 90°C.

4. Conclusions.

The work aims to develop a mathematical method that allows determining the temperature of an electrical cable buried in the ground, inserted inside a protective tube, depending on the value of the working current.

It was intended to highlight the way in which heat transfer occurs, determine the conductor temperature and the temperature distribution in the wall of the protective tube in contact with the ground.

Starting from the analogy with heat transfer through extended surfaces (flat fins), easy-to-use calculation relationships were obtained, which take into account the properties and dimensions of the conductor, insulation, protective tube and ground.

The model was used to study a medium voltage (MV) cable, with a single multi-wire aluminium conductor, type NA2XSYP 12/20 kV, from the current production of the Romanian company IPROEB – Bistrița. The coincidence of the results with the manufacturer's specifications shows that the model is correct and can be used for the study of the thermal regime of conductors buried in the ground.

References.

- [1] *** IEC 60287 – „Electric Cables–Calculation of the Current Rating”, International Electrotechnical Commission, 2019.
- [2] Anders G.J. „Rating of Electric Power Cables in Unfavourable Thermal Environment”- IEEE Press, 2005, USA. ISBN 0-47 1-67909-7
- [3] Rerak M., Ochoń P., „Thermal Analysis of Underground Power Cable Systems”, J. of Thermal Sci., Iss. 26, 2017, pp. 465-471. DOI:[10.1007/S11630-017-0963-2](https://doi.org/10.1007/S11630-017-0963-2)
- [4] *** EEA - „Soil Thermal Properties and Their Influence on Underground Cables”, European Environment Agency, 2022.
- [5] *** IEEE PES - „Underground Distribution Systems – Failure Mechanisms and Fire Risk”, IEEE Power & Energy Society, 2018.
- [6] ***UNEP - „Toxic Emissions from Polymer Decomposition”, United Nations Environment Programme, 2021.
- [7] *** CIGRÉ - Technical Brochure 825 – „Fire Risk in Underground Electrical Installations”, 2021.
- [8] *** ITF/OECD - „Thermal Backfill Materials for Power Cables”, 2023.
- [9] Lipan L.L., Dimitriu S., Sbora L.M., „Power factor in installations with non-linear receivers and heating elements of the power cables of various equipment”, UPB Sci. Bull., Series C, Vol. 84, Iss. 1, 2022, pp. 261-274, ISSN 2286-3540
- [10] Sbora L.M., Dimitriu S. Pavel D.I., Lipan L.C., „Starting fires in electrical switchboards and extinguishing them” - UPB Sci. Bull, seria C, vol.85, Iss 2, 2023, pp. 349-365, ISSN 2286-3540.
- [11] Hannun R. M., „Thermal Analysis for Underground Power Cables with Different Arrays in Hot Places”, Thi Qar Univ. Journal for Eng. Sciences, vol.9, Iss.2, 2018, pp. 109-117, DOI:[10.31663/tqujes.9.2.329](https://doi.org/10.31663/tqujes.9.2.329)2018.
- [12] Vollaro R.L., Fontana L., Vallati A., „Thermal analysis of underground electrical power cables buried in non-homogeneous soils”, ELSEVIR, App. Thermal Eng., Iss. 31, 2011, pp. 772-778, DOI: [10.1016/j.applthermaleng.2010.10.024](https://doi.org/10.1016/j.applthermaleng.2010.10.024)
- [13] *** IPROEB S.A. – „Catalogul de cabluri izolate”. Bistrița: IPROEB, 2010, pp.119, pp.212. Available to: [cabluri izolate complet.pdf](#) .

TRNSYS - Dynamic Simulation of a Three-Zone House in Iași Heated and Cooled by an Air-Source Heat Pump

Simularea dinamică în TRNSYS 18 a unei case cu trei zone din Iași încălzită și răcită cu o pompă de căldură aer-sursă

Cătălin Vulpe¹, Radu Panduru¹, Marius Alexa¹, Marina Verdeș¹, Sebastian-Valeriu Hudișteanu¹, Nelu Cristian Cherecheș¹, Florin Emilian Țurcanu¹, Claudiu Romila¹, Cătălin George Popovici¹, Vasilică Ciocan¹, Diana-Ana Ancaș¹

¹ Gheorghe Asachi” Technical University of Iași
Bulevardul Profesor Dimitrie Mangeron 67, 700050 Iași, Romania
E-mail: florin-emilian.turcanu@academic.tuiasi.ro

DOI: 10.37789/rjce.2026.17.3.8

Abstract: *This paper presents a TRNSYS 18 dynamic model of a three-zone dwelling in Iași, Romania, with a conditioned floor area of 224 m² and an enclosed volume of 747 m³. The model couples climate processing, solar-radiation conversion, ground interaction, a TRNBUILD multizone building, a thermostat, and an air-source heat pump. Using the uploaded annual plots, the study interprets incident solar radiation, indoor/outdoor temperatures, zone-specific heating and cooling loads, and heat-pump electricity use. The original contribution is the explicit mapping between TRNSYS component outputs and engineering indicators, together with a discussion of the current model-coupling limits and the pathway toward PV-battery integration.*

Key words: TRNSYS 18, air-source heat pump, residential building, heating and cooling loads

1. Introduction

Buildings remain a central energy and climate challenge. According to the International Energy Agency (IEA), building operations account for around 30% of global final energy consumption and 26% of global energy-related emissions, which makes the decarbonization of building services a strategic research priority [1]. In advanced economies, space and water heating still represent the dominant share of residential energy use [1]. Heat pumps are among the most promising electrification technologies for this transition. The IEA shows that heat pumps powered by low-emissions electricity are a central option for secure and sustainable heating, and that currently available units are typically three to five times more energy efficient than natural-gas boilers [2]. Their dual capability for space heating and cooling is especially

relevant for climates with both winter heating demand and increasingly important summer overheating periods [2]. For dynamic research problems that couple the building envelope, weather, control logic, renewable electricity and HVAC equipment, TRNSYS is particularly appropriate. The software is an iterative, component-based transient simulation environment widely used for thermal and electrical energy systems [3]. Within the standard library, TRNBUILD is the multizone building model linked to a TRNBuild description file, while the component library also supports ground-coupled boundary models and HVAC components [4].

The scientific literature already confirms the relevance of combining heat pumps with solar electricity and storage. Jonas et al. showed how TRNSYS can be used to model solar-thermal and heat-pump system configurations [5]. Bee et al. developed a TRNSYS model of a single-family house equipped with an air-source heat pump and photovoltaic system, highlighting the role of storage in self-consumption [6]. More recently, Gagliano et al. reported strong improvements in residential self-consumption and self-sufficiency when heat pumps were combined with electrical and thermal storage [7].

Similar conclusions were reached for net-zero-oriented residential PV–heat-pump sizing studies [8] and for hybrid battery concepts aimed at increasing photovoltaic self-consumption [9]. Review work also indicates that heat-pump systems integrated with solar technologies and storage are a robust pathway toward nearly zero-energy buildings [10]. Against this background, the objective of the present paper is to document and interpret a user-provided TRNSYS 18 model of a house located in Iași, Romania, with a total floor area of 224 m² and an enclosed volume of 747 m³. The manuscript follows the uploaded conference template and uses the attached TRNSYS scheme and annual plots to discuss (i) the structure of the simulation model, (ii) the equations used to convert raw TRNSYS outputs into engineering indicators, (iii) the annual behavior of solar forcing, indoor temperatures, zone-specific heating/cooling demands, and heat-pump electrical demand, and (iv) the implications of the current results for a future PV–battery extension of the model. Because the uploaded figure set does not include raw battery plots, the battery-related part is developed here as a model-ready framework rather than as a quantified annual result.

2. Content of the paper

2.1. Case study and TRNSYS model architecture

The uploaded case-study descriptor identifies a residential building placed in Iași, Romania, with a conditioned surface of 224 m² and a total enclosed volume of 747 m³. The TRNBuild screen capture shows a three-zone configuration, while the post-processing equations used in the Simulation Studio model indicate zone floor areas of 64 m² for Zone 1, 64 m² for Zone 2 and 96 m² for Zone 3. The annual simulation horizon is 8760 h, as confirmed by the horizontal axes of the uploaded online plotters.

The Simulation Studio scheme contains the following functional blocks: a settings block, a climate block, a radiation unit converter, a ground-coupled boundary/ground-

solar block, the multizone building block, an air-source heat pump, a room thermostat, a unit converter for post-processing, and four online plotters dedicated to solar radiation, temperatures, specific heating/cooling loads, and electrical power. The building block is consistent with TRNBUILD because the uploaded output list includes the standard TRNBUILD variables TAIR, TOP, QHEAT, QCOOL, QELEQUIP, and QELIGHT for each thermal zone.

The climatic data feed both the solar and thermal boundary conditions. The uploaded solar plot shows that the model tracks several surface orientations, including horizontal and tilted south, east, west, and north-facing surfaces. The ground-coupled block supplies a boundary temperature for the floor-side coupling, while the weather signals and the building state variables are exchanged with the heat pump and controller.

2.2. Control and post-processing logic

The room thermostat monitors room temperature and sends heating, cooling and conditioning control signals to the air-source heat pump. In parallel, the TRNBUILD building model provides ideal-load outputs for zone-level space heating and cooling. For publication purposes, the raw TRNSYS outputs were converted into specific loads (W/m^2) and electrical powers (kW) through a dedicated unit converter. This post-processing is important because the original building outputs are reported in kJ/h, while the heat-pump power outputs are also reported in kJ/h in the uploaded project configuration. The manuscript intentionally keeps the distinction between ideal building loads and physical plant-side electricity demand. The annual heating and cooling curves are derived from the building model (ideal zone loads), whereas the electricity plot is derived from the heat-pump block. This distinction is important when discussing model maturity: the envelope and ideal-load submodel can already be interpreted with confidence, while the plant-side annual synchronization still requires refinement before seasonal COP or PV-battery self-sufficiency indicators are reported.

2.3. Control and post-processing logic

The solar-radiation plot confirms a strong seasonal and orientation-dependent variability of the climate input in Iași. Graphical reading of the uploaded annual plot suggests that the maximum total and beam incident solar radiation approaches 1000 W/m^2 for the most favorably exposed surfaces during the warm season. This result is fully consistent with the need to represent separate facade and roof orientations when assessing mixed heating-cooling behavior. The temperature plot shows a large outdoor thermal amplitude, with ambient temperature visually ranging from approximately -15°C in winter to about 36°C in summer. In contrast, the zone air and operative temperatures remain in a much narrower band, generally clustering around roughly $18\text{--}26^\circ\text{C}$. The three thermal zones follow similar seasonal trends, but they are not

perfectly identical, which reflects both the zoning choices and the differences in exposed surfaces and roof participation visible in the TRNBuild model. The heating/cooling plot indicates a clearly heating-dominated annual behavior. The highest specific heating demand is observed in Zone 2, with graphical peaks close to 95–100 W/m², followed by Zone 3 at about 85–90 W/m² and Zone 1 at approximately 60–65 W/m². Cooling appears mainly during the middle of the year and is smaller in magnitude, with the most exposed zone reaching about 50–55 W/m² and the remaining zones typically remaining below about 25 W/m². The figure, therefore, shows that the building is substantially more constrained by winter heating than by summer cooling under the uploaded configuration. The electrical plot reveals that the compressor power during active periods is around 1.5–1.6 kW, while the total heat-pump electric power is almost superposed on the compressor curve. This suggests that fan contributions are comparatively small under the current operating conditions. However, the electrical activity appears concentrated only in part of the annual horizon, whereas the ideal-load plot exhibits both winter heating and summer cooling seasons. Scientifically, this mismatch is a useful result: it indicates that the present model already supports envelope-level and ideal-load analysis, but the full year-round coupling between TRNBUILD loads and the heat-pump control should still be refined before reporting annual system performance factors, grid exchange metrics or final battery self-sufficiency indicators.

2.4. Control and post-processing logic

The wider research objective indicated by the authors concerns a fully electrified residential system extended with photovoltaic generation and electrical storage. In that context, the current model is already suitable as the thermal core of the future study because it provides hourly weather forcing, thermal-zone demand, and plant-side power signals. The battery state of charge, production-consumption balance, excess electricity and grid exchange can therefore be added consistently on top of the present framework. Because the uploaded figure set available for this article does not contain explicit battery plots, the battery part is formulated below through general governing equations and discussed as an immediate continuation of the validated thermal model, not as a completed quantitative result.

3. Equations

The main equations used for the interpretation of the uploaded TRNSYS results are listed below. Equations (1)–(3) describe the generic thermal-control logic, Equations (4)–(7) reproduce the exact engineering post-processing used in the uploaded TRNSYS model, and Equations (8)–(9) provide the battery-ready extension for the future integrated electric system.

$$C_z dT_z/dt = \sum_j U_j A_j (T_{\{s,j\}} - T_z) + \dot{m}_{\{inf,z\}} c_p (T_{\{amb\}} - T_z) + \dot{Q}_{\{sol,z\}} + \dot{Q}_{\{int,z\}} + \dot{Q}_{\{HVAC,z\}} \quad (1)$$

$$u_{\{h,z\}} = 1, \text{ if } T_{\{air,z\}} < T_{\{set,h\}}; \quad u_{\{h,z\}} = 0, \text{ otherwise} \quad (2)$$

$$u_{\{c,z\}} = 1, \text{ if } T_{\{air,z\}} > T_{\{set,c\}}; \quad u_{\{c,z\}} = 0, \text{ otherwise} \quad (3)$$

$$q_{\{ht,z\}} = Q_{HEAT_z} / (3.6 A_z), \text{ with } A_1 = 64 \text{ m}^2, A_2 = 64 \text{ m}^2, A_3 = 96 \text{ m}^2 \quad (4)$$

$$q_{\{cl,z\}} = Q_{COOL_z} / (3.6 A_z) \quad (5)$$

$$P_{\{comp\}} = \text{Compressor Power} / 3600, \quad P_{\{el,tot\}} = \text{Total Energy Input} / 3600 \quad (6)$$

Implemented TRNSYS converter equations: $q_{ht_1}=[56,3]/3.6/64$; $q_{cl_1}=[56,4]/3.6/64$;
 $q_{ht_2}=[56,9]/3.6/64$; $q_{cl_2}=[56,10]/3.6/64$; $q_{ht_3}=[56,15]/3.6/96$;
 $q_{cl_3}=[56,16]/3.6/96$; $HP_comp_kW=Input1/3600$; $HP_total_kW=Input2/3600$ (7)

$$SOC_{\{k+1\}} = SOC_k + \eta_{\{ch\}} P_{\{ch\}} \Delta t / E_{\{bat\}} - P_{\{dis\}} \Delta t / (\eta_{\{dis\}} E_{\{bat\}}) \quad (8)$$

$$P_{\{PV\}} + P_{\{grid\}} + P_{\{dis\}} = P_{\{HP\}} + P_{\{aux\}} + P_{\{ch\}} + P_{\{exp\}} \quad (9)$$

Main symbols: A_z – floor area of zone z ; C_z – effective thermal capacitance of zone z ; c_p – specific heat of air; E_{bat} – nominal battery capacity; $\dot{m}_{inf,z}$ – infiltration mass-flow rate; P_{ch}/P_{dis} – charge/discharge power; P_{exp} – exported electrical power; P_{grid} – imported grid power; P_{HP} – heat-pump electrical demand; $\dot{Q}_{HVAC,z}$ – heat added to or removed from zone z ; $q_{ht,z}$ and $q_{cl,z}$ – specific heating and cooling loads; SOC – battery state of charge; $T_{air,z}$ – zone air temperature; $T_{set,h}$ and $T_{set,c}$ – heating and cooling setpoints.

4. Tables

The main input data, variable mappings and graphically interpreted annual results are summarized in the following tables.

Table 1

Case-study building and simulation information

Item	Value
Location / Conditioned floor area	Iași, Romania / 224 m ²
Enclosed volume / Number of thermal zones	747 m ³ / 3
Zone floor areas	Zone 1 = 64 m ² ; Zone 2 = 64 m ² ; Zone 3 = 96 m ²
Building model / Plant model	TRNSYS TRNBUILD / TRNBuild multizone building / Air-source heat pump with room thermostat
Boundary-condition processing / Simulation horizon	Climate block, radiation unit converter, and ground-coupled/ground-solar block / 8760 h (annual)

Item	Value
Main reported outputs	Incident solar radiation, ambient and indoor temperatures, specific heating/cooling loads, heat-pump electric power

Table 2

TRNSYS output mapping and post-processing equations used in the article

Indicator	TRNSYS origin	Post-processing equation	Final unit
q _{ht,1}	TRNBUILD output [56,3]	[56,3]/3.6/64	W/m ²
q _{cl,1}	TRNBUILD output [56,4]	[56,4]/3.6/64	W/m ²
q _{ht,2}	TRNBUILD output [56,9]	[56,9]/3.6/64	W/m ²
q _{cl,2}	TRNBUILD output [56,10]	[56,10]/3.6/64	W/m ²
q _{ht,3}	TRNBUILD output [56,15]	[56,15]/3.6/96	W/m ²
q _{cl,3}	TRNBUILD output [56,16]	[56,16]/3.6/96	W/m ²
HP_comp_kW	Unit converter Input1 from Compressor Power	Input1/3600	kW
HP_total_kW	Unit converter Input2 from Total Energy Input	Input2/3600	kW

Table 3

Approximate annual results graphically interpreted from the uploaded TRNSYS plots

Variable / indicator	Approximate graphical value	Interpretation
Maximum total / beam incident solar radiation	up to ~1000 W/m ²	Strong summer solar availability and strong orientation dependence.
Outdoor ambient air temperature	Approximately -15 °C to 36 °C	Cold-heating and warm-cooling seasons are both present in Iași climate conditions.
Zone air / operative temperature band	Mostly ~18 °C to 26 °C	Indoor temperatures vary much less than ambient temperature, confirming the moderating effect of the envelope and ideal-load control.
Peak specific heating load – Zone 1	about 60–65 W/m ²	Heating demand is high in winter but lower than in Zones 2 and 3.
Peak specific heating load – Zone 2	about 95–100 W/m ²	Zone 2 is the most heating-demanding zone in the current configuration.
Peak specific heating load – Zone 3	about 85–90 W/m ²	Zone 3 also has strong winter demand, slightly below Zone 2.
Peak specific cooling load –	about 50–55 W/m ²	Cooling is present mainly in the middle of the year

Variable / indicator	Approximate graphical value	Interpretation
most exposed zone		and remains lower than winter heating.
Heat-pump compressor power during active periods	about 1.5–1.6 kW	Electrical power is dominated by compressor demand.
Difference between total and compressor electric power	very small in the uploaded plot	Fan contributions appear modest compared to compressor power.

Table 4

Melting points and basic analyzes

Compuși	Mp(°C)	Formula chimică	N(%)	
			Calc.	Rezultat
3A	178	C ₂₉ H ₃₄ N ₂ O	6.57	6.70
3B	264	C ₂₉ H ₃₃ N ₃ O ₃	8.92	8.85
3C	232	C ₂₉ H ₃₂ N ₄ O ₅	10.85	10.78
5A	185	C ₂₉ H ₃₄ N ₂ O	6.56	6.41
5B	242	C ₂₉ H ₃₃ N ₃ O ₃	8.92	8.87
5C	245	C ₂₉ H ₃₂ N ₄ O ₅	10.85	10.63

5. Figures

The figures below are reproduced from the uploaded TRNSYS project material and the corresponding online plotter screenshots.

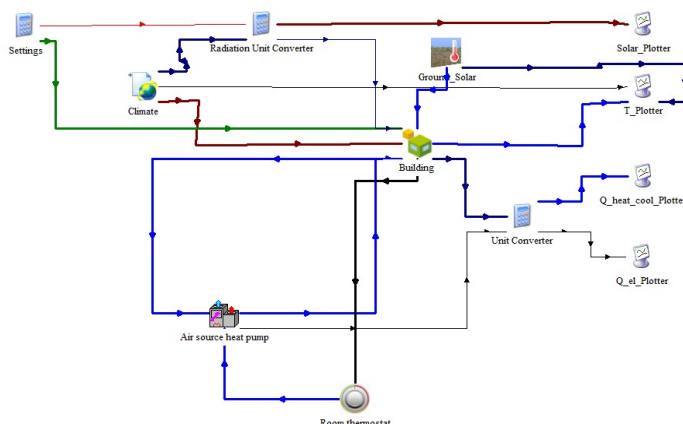


Fig. 1. TRNSYS 18 Simulation Studio scheme used for the case-study building, including climate processing, radiation conversion, ground interaction, multizone building model, room thermostat, air-source heat pump, and online plotters.

Each figure is announced by an insertion marker, as requested, and is followed by its centered caption.

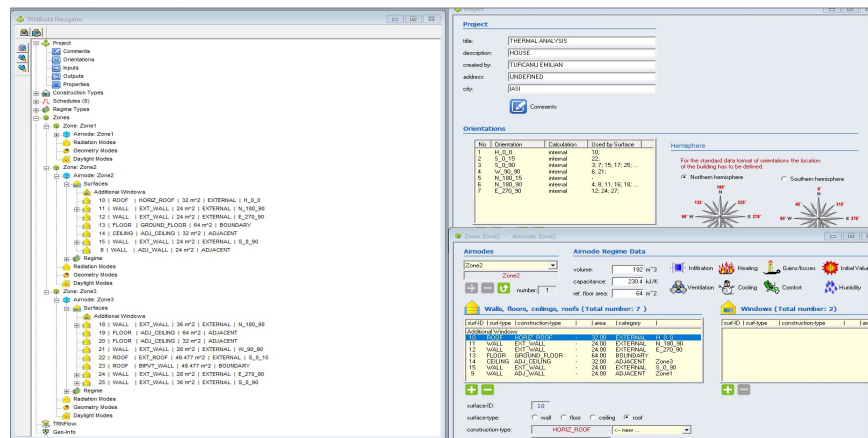


Fig. 2. TRNBuild view of the case-study building, showing the project setup, zone structure, orientations, and surface definitions used to generate the TRNBUILD building description file.

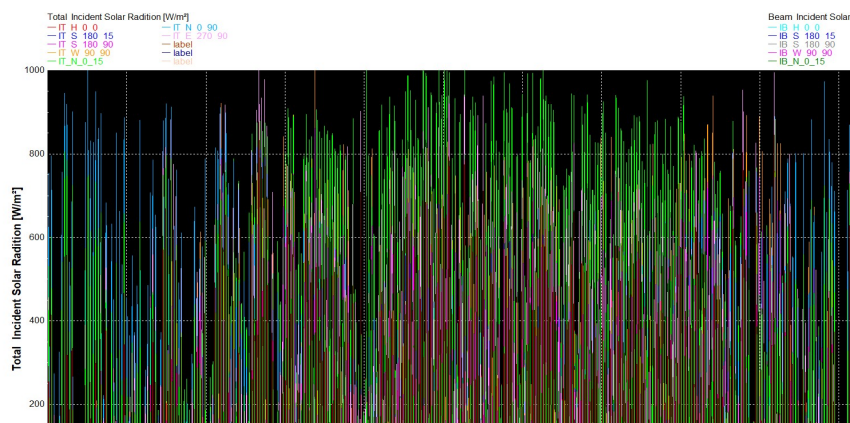


Fig. 3. Annual total and beam incident solar radiation on the modeled orientations, as provided by the TRNSYS online solar plotter.

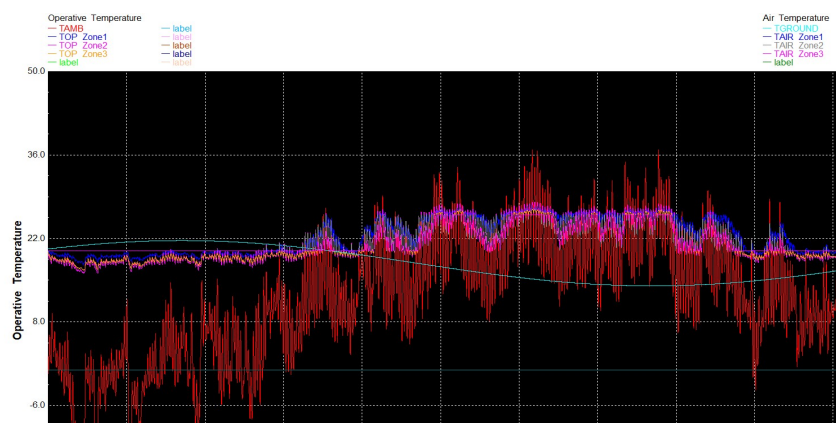


Fig. 4. Annual outdoor ambient temperature together with the air and operative temperatures of the three thermal zones.

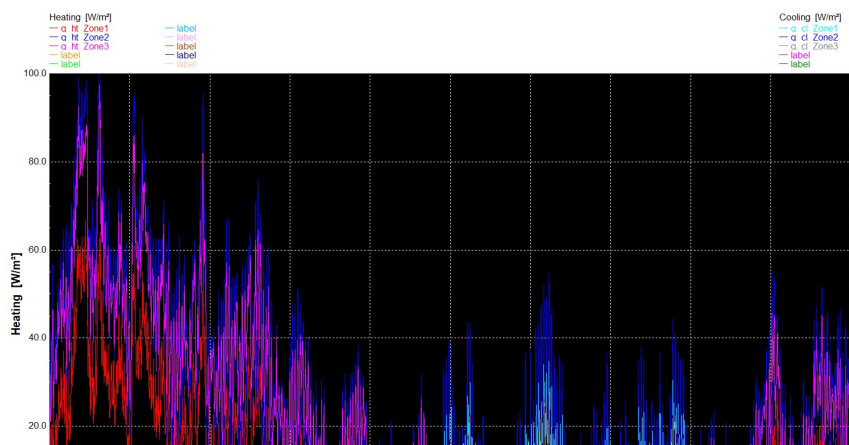


Fig. 5. Annual specific heating and cooling loads of the three zones, post-processed from the TRNBUILD building outputs.

6. Conclusions

The uploaded TRNSYS 18 model supports a coherent dynamic interpretation of a three-zone residential building located in Iași, Romania. The building-level part of the model is already mature enough to provide meaningful annual results for incident solar radiation, indoor thermal response, and zone-specific space-conditioning loads.

The annual plots show a clearly heating-dominated case study. Specific winter heating peaks are strongest in Zone 2, followed by Zone 3, while summer cooling is present over a shorter period and at smaller magnitudes. The ambient climate exhibits a broad annual range, but the indoor temperatures remain confined to a much narrower interval, confirming the damping effect of the envelope and the ideal-load formulation in the building model.

The air-source heat pump electrical plot indicates active compressor demand of roughly 1.5–1.6 kW during the operating windows captured by the uploaded results, while the total electrical power almost overlaps the compressor curve. This suggests that the compressor dominates the electric consumption under the current operating conditions.

At the same time, the uploaded figures reveal an important modeling insight: the ideal TRNBUILD thermal loads and the physical heat-pump electrical activity are not yet fully synchronized over the entire year. Therefore, the current project version is scientifically suitable for envelope/load analysis and controller debugging, but it should be further refined before deriving annual SPF/COP, grid-exchange or battery-autonomy indicators from the same coupled deck.

The next research step is straightforward: the validated thermal core can be extended with photovoltaic generation, electrical storage, state-of-charge tracking, production-consumption balance, and excess-energy indicators. Once the battery plots or raw hourly output files are exported from TRNSYS, the manuscript can be extended

from the present thermal-and-plant assessment to a full PV–battery–heat-pump self-consumption and self-sufficiency study.

References

- [1] IEA, “Buildings - Energy System”, International Energy Agency, Paris, 2025, available online: <https://www.iea.org/energy-system/buildings>.
- [2] IEA, “The Future of Heat Pumps”, International Energy Agency, Paris, 2022, available online: <https://www.iea.org/reports/the-future-of-heat-pumps>.
- [3] TRNSYS, “Welcome | TRNSYS: Transient System Simulation Tool”, Thermal Energy System Specialists, Madison, WI, available online: <https://www.trnsys.com/>, accessed March 2026.
- [4] TRNSYS, “TRNSYS 18 – Standard Component Library Overview”, Thermal Energy System Specialists, Madison, WI, available online: <https://www.trnsys.com/assets/docs/03-ComponentLibraryOverview.pdf>, accessed March 2026.
- [5] D. Jonas, D. Theis, F. Felgner, G. Frey, “A TRNSYS-based simulation framework for the analysis of solar thermal and heat pump systems”, *Applied Solar Energy*, vol. 53, 2017, pp. 126-137.
- [6] E. Bee, A. Prada, P. Baggio, E. Psimopoulos, “Air-source heat pump and photovoltaic systems for residential heating and cooling: Potential of self-consumption in different European climates”, *Building Simulation*, vol. 12, 2019, pp. 453-463.
- [7] A. Gagliano, G.M. Tina, S. Aneli, “Improvement in Energy Self-Sufficiency in Residential Buildings Using Photovoltaic Thermal Plants, Heat Pumps, and Electrical and Thermal Storage”, *Energies*, vol. 18, no. 5, 2025, article 1159.
- [8] S. Rana, U. Jamil, N. Asgari, K.S. Hayibo, J. Groza, J.M. Pearce, “Residential Sizing of Solar Photovoltaic Systems and Heat Pumps for Net Zero Sustainable Thermal Building Energy”, *Computation*, vol. 12, no. 6, 2024, article 126.
- [9] A. López-Ceballos, C. del Cañizo, I. Antón, A. Datas, “Integrating lithium-ion and thermal batteries with heat pumps for enhanced photovoltaic self-consumption”, *Applied Energy*, vol. 390, 2025, article 125767.
- [10] A. Miglioli, N. Aste, C. Del Pero, F. Leonforte, “Photovoltaic-thermal solar-assisted heat pump systems for building applications: Integration and design methods”, *Energy and Built Environment*, vol. 4, no. 1, 2023, pp. 39-56.

Night Ventilation as a Key Strategy for Enhancing HVAC Energy Efficiency in Educational Buildings: A Case Study of Energy Savings

Ventilarea de noapte ca strategie cheie pentru creșterea eficienței energetice a sistemelor HVAC în clădirile educaționale: Un studiu de caz privind economiile de energie

Marius Adam¹, Adriana Tokar¹, Alexandru Dorca¹, Dănuț Tokar¹

¹ Politehnica University of Timisoara

Victoriei Square, Nr.2, Timisoara, Romania

E-mail: marius.adam@upt.ro, adriana.tokar@upt.ro, alexandru.dorca@upt.ro, danut.tokar@upt.ro

DOI: 10.37789/rjce.2026.17.3.9

Abstract: Educational buildings frequently face issues with overheating and high energy consumption associated with HVAC systems, amid rising global temperatures and increasing demands for thermal comfort. Night Ventilation (NV) has been recognized as an effective passive or semi-passive cooling technique that utilizes cooler outdoor air to discharge the building's thermal mass during the night, thereby creating a 'cool reservoir' for the following day. This article presents a case study on the implementation of night ventilation strategies in an educational building, aiming to evaluate energy efficiency and the impact on thermal comfort. The study analyzes the interaction between night ventilation rates, building thermal inertia, and the energy consumption of HVAC equipment during occupancy periods. The results demonstrate that an optimized night ventilation strategy can significantly reduce peak cooling loads and the number of thermal discomfort hours. Furthermore, the paper explores the economic cost-benefit ratio by comparing the energy consumption of fans during the night with the savings generated by the reduced use of HVAC systems during the day. The study emphasizes that, although night ventilation cannot always independently ensure full thermal comfort, its integration as part of a hybrid cooling system is a feasible and energy-efficient solution for educational buildings.

Key words: Night ventilation; HVAC efficiency; educational buildings; thermal mass; energy savings; thermal comfort

1. Introduction and theoretical basis

The link between thermal inertia, night ventilation (also known as free cooling or night cooling) and the electrical energy consumption of HVAC equipment represents one of the most effective design principles for sustainable buildings[1,5].

The operating principle is based on the ability of massive building elements (such as concrete or brick) to absorb heat generated internally or from solar radiation during the day, a phenomenon described as thermal inertia. At night, when the outside air is colder, the ventilation system introduces this air to “unload” the structure thermally. Thus, the building starts the next day with a lower internal temperature, drastically reducing the need for the compressors of the cooling systems [2].

The heat transfer mechanism is governed by the following mathematical equations:

- *thermal mass storage capacity:*

$$Q_{masă} = m \cdot c_p \cdot \Delta T_{structură} \quad (1)$$

- *energy extracted through night ventilation:*

$$Q_{vent} = L \cdot \rho_{aer} \cdot c_{p,aer} \cdot (T_{int} - T_{ext}) \cdot t \quad (2)$$

- *theoretical energy savings on HVAC equipment:*

$$E_{răcire_{evitată}} = \frac{Q_{vent}}{SEER} \quad (3)$$

- *energy consumption of fans:*

$$E_{ventilatoare} = SFP \cdot L \cdot t \quad (4)$$

where:

Q_{mass} – thermal energy stored in the mass of the building (J);

m – mass of thermally active building elements (kg);

c_p – specific heat capacity of building materials (J/kg·K);

$\Delta T_{structure}$ – temperature difference of the thermal mass between day and night regime (K);

Q_{vent} – extracted thermal energy (J);

L – fresh air volume flow rate (m³/s);

ρ_{air} – air density (kg/m³);

$c_{p,air}$ – specific heat of air (J/kg·K);

$T_{int} - T_{ext}$ – temperature difference between the exhaust indoor air and the introduced outdoor air (K);

t – operating time of night ventilation (s);

$SEER$ – seasonal energy efficiency of the VRV system.

For night ventilation to be considered energy efficient, the energy saved by not using the cooling compressor must be strictly greater than the energy consumed by the fans to move the air during the night [3,4]:

$$E_{economie_netă} = E_{răcire_evitată} - E_{ventilatoare} > 0 \quad (5)$$

2. Experimental setup: ventilation laboratory

The case study was carried out in an educational experimental room (fig.1), with the following geometric characteristics: length 10.3 m, width 6.6 m, height 3.75 m, resulting in a useful surface area of 68 m² and an air volume of 255 m³.

The space has a significant thermal mass, necessary for heat storage. The floor and the floor are made of 20 cm of concrete, 5 cm of screed and 1 cm of sandstone. The east-facing exterior wall, made of 25 cm solid brick masonry, contains a large glazed surface (25 m²), while the south-facing wall is also made of 25 cm solid brick. These heavy materials act as a thermal flywheel, quantitatively evaluated by the thermal inertia index. Two systems are used for air conditioning:

Ventilation system (CTA): a GEA CAIRplus SX air handling unit, with a nominal flow rate of 8000 m³/h and a specific fan power indicator $SFP = 1.37 \text{ kW}/(\text{m}^3/\text{s})$.

Air conditioning system (VRV): a Daikin RSX inverter system, necessary to cover a maximum cooling load calculated at 9501.49 W.

According to literature recommendations for schools and medium-sized spaces, the ideal air change rates (ACH) for night ventilation are between 5 and 15 ACH.

2.1. Viewing the 3D model of the experimental room

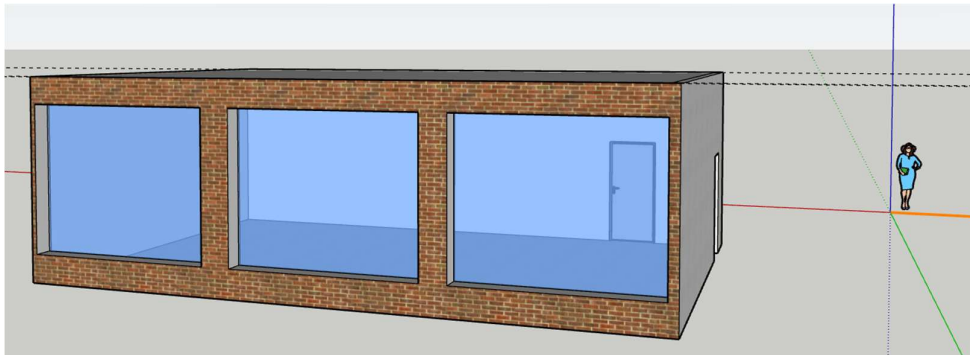


Fig. 1. 3D model of the experimental room – the ventilation laboratory

The 3D model of the ventilation laboratory clearly highlights the orientation and composition of the walls. The East wall features a major glazed area of 25 m², framed by 25 cm solid brickwork. This architectural configuration allows for massive diurnal solar heat gain. The heat radiated into the interior is efficiently stored throughout the day in the thermal mass of the floor, concrete floor and interior walls.

3. Case study and in situ measurements

To validate the efficiency of the strategy, comparative measurements were carried out on two consecutive days in June 2025, simulating similar occupancy conditions (10 people present during the day).

Scenario A (without night ventilation) – 06.06.2025: the building did not benefit from night free cooling. The VRV system was started at 08:00 (meter index 44.45 kWh) and operated until 16:00 (meter index 62.61 kWh). The indoor temperature was maintained around 26.5°C, but the thermal mass warmed up significantly, with the floor temperature reaching 24.8°C at 16:00.

Scenario B (with night ventilation) – 07.06.2025: a night ventilation strategy was implemented between 04:00 and 07:30, operating the AHU at a constant flow rate of 1500 m³/h. Subsequently, the VRV system was used from 08:00 (index 63.65 kWh) to 15:30 (index 75.11 kWh).

Tabelul 1

Sinteza parametrilor în timpul ventilației de noapte (07.06.2025, extrase)

Ora	Contor CTA (kWh)	Text (°C)	Tint (°C)	Efect asupra camerei
04:00	7.00	21.0	26.4	Pornire NV
06:00	8.22	21.0	25.0	Răcire progresivă
07:30	8.93	21.3	23.4	Oprire NV

At the end of the free cooling cycle, the indoor air temperature dropped from 26.4°C to 23.4°C.

4. Data analysis and application of mathematical formulas

Using measurements, we can validate the theoretical mathematical model.

- **Evaluating the air exchange rate (ACH)** at a flow rate $L=1500$ m³/h and a room volume of 255 m³, we have: $ACH = 5.88$ hourly changes. This value falls perfectly within the optimal range of 5-15 ACH recommended for educational buildings.

- **Modeling the Consumption of Fans (E_{fans})**, according to formula (4) and using the values for $SFP = 1.37$ KW/(m³/s), $L=0.416$ m³/s and the time of 3.5 hours, resulted in: $E_{ventilatoare} = 1,37 \cdot 0,416 \cdot 3,5 = 1,99$ kWh.

This theoretical result is extremely accurate validated by the actual meter index: 8.93 kWh-7.00 kWh = 1.93 kWh actually consumed.

- **Energy balance and net savings ($E_{\text{net_savings}}$)** the consumption of VRV equipment to provide air conditioning during the day has changed drastically due to the pre-cooling of the thermal mass:

VRV consumption without NV (06.06.2025, 8h operation): 62.61-44.45=18.16 kWh

VRV consumption with NV (07.06.2025, 7.5h operation): 75.11-63.65=11.46 kWh.

Gross savings on cooling equipment, $E_{\text{avoided_cooling}}$ =18.16-11.46=6.70 kWh.

Net energy savings (5) is: $E_{\text{net_savings}}$ =6.70-1.93=4.77 kWh/day.

- **Impact on thermal inertia**, the effect is directly observed at the level of the building elements. At the end of the program on 07.06.2025 (with NV), the concrete floor reached 23.6°C, compared to 24.3°C recorded on the day without night ventilation. The same mass cooling phenomenon is also visible on the inner surface of the sheet metal wall (decrease from 25.7°C to 24.2°C).

5. Conclusions and future research directions

The case study demonstrates mathematically and empirically that night ventilation is a viable strategy for Romanian educational buildings, managing, in a typical summer scenario, to reduce the electrical energy consumption of the VRV system by almost 37% (from 18.16 kWh to 11.46 kWh). By reducing the adjacent consumption of ventilation equipment (1.93 kWh), a clear net energy saving results, perfectly fulfilling the theoretical condition: $Q_{\text{vent}}/SEER > SFP \cdot L \cdot t$. Beyond the energy savings, the unloading of the thermal mass of the concrete prevents sudden jumps in radiated temperature, directly improving the comfort of the students.

Based on the findings from recent literature and previous theoretical discussions, the following directions for developing this topic are proposed:

Assessing the resilience of night ventilation to future climate change: analyzing how the future increase in ambient temperatures during the night will diminish the potential of the Q_{vent} equation, imposing either much higher flow rates (with a penalty on the SFP), or creating exclusively hybrid systems.

Optimizing operating parameters using predictive algorithms (machine learning): avoiding "supercooling" and optimizing the time, t , in formula (4) by coupling sensors with predictive weather models, so that the energy consumed by the AHU is exactly the minimum necessary to discharge the thermal mass.

Correlating acoustic interfaces with thermal inertia: considering that the educational environment requires acoustic ceilings (which often cover the concrete floor, blocking storage), future studies can analyze the integration of radiant panels or diffuse ceilings with slots, so as not to sacrifice the thermal flywheel effect.

References

- [1] Rui Guo, Yue Hu, Per Heiselberg, Hicham Johra, Chen Zhang, Pei Peng, “Simulation and optimization of night cooling with diffuse ceiling ventilation and mixing ventilation in a cold climate”, *Renewable Energy* 179 (2021) 488-501.
- [2] Donal P. Fin, Darragh Connolly, Paul Kenny, “Sensitivity analysis of a maritime located night ventilated library building”, *Solar Energy* 81 (2007) 697–710.
- [3] Wenhui Ji, Houhua Wang, Tao Du, Zili Zhang, “Parametric study on a wall-mounted attached ventilation system for night cooling with different supply air conditions”, *Renewable Energy* 143 (2019) 1865-1876
- [4] Miguel Lança, Pedro J. Coelho, João Viegas, “Numerical simulation of a night cooling strategy in an office room”, *Energy & Buildings* 252 (2021) 111359.
- [5] Marius Adam, Adriana Tokar, Alexandru Dorca, Dănuț Tokar, Alexandru Filipovici, “A general review on night ventilation systems used to reduce energy consumption in buildings”, *Romanian Journal of Civil Engineering*, Volume 16 (2025), Number 3.

Decentralized Rainwater Management for Urban Resilience: Principles, Policy Context and a Case Study from Romania

Managementul descentralizat al apei meteorice pentru reziliența urbană: principii, context politic și un studiu de caz din România

Cristina Iacob¹, Anagabriela Deac¹, Dan Mureșan¹, Teodor Chira¹

¹ Technical University of Cluj-Napoca

St. Memorandumului 28, Cluj-Napoca, Romania

E-mail: cristina.iacob@insta.utcluj.ro, anagabriela.deac@insta.utcluj.ro,

muresan.dan@insta.utcluj.ro, teodor.chira@insta.utcluj.ro

DOI: 10.37789/rjce.2026.17.3.10

Abstract: *Urban areas face growing flood risks and hydraulic overloads due to climate change, urban densification, and the expansion of impervious surfaces. In this context, decentralized rainwater management is increasingly recognized as a valuable complement to conventional drainage systems. This paper outlines the principles and policy context of decentralized rainwater harvesting and infiltration, with a focus on nature-based and building-scale solutions that align with European water policies. The practical application of these approaches is illustrated through a case study of a decentralized rainwater harvesting and infiltration system implemented in an educational building in Cluj-Napoca, Romania. The findings demonstrate that such systems can reduce stormwater discharge, support non-potable water reuse, and improve urban water resilience.*

Key words: decentralized rainwater management; stormwater management; urban resilience; nature-based solutions; rainwater harvesting; infiltration systems

1. Introduction

Urban areas are facing growing water-related challenges driven by climate change, rapid urbanization, and the expansion of impervious surfaces. These factors lead to higher stormwater runoff volumes, increased flood risk, and greater pressure on centralized drainage and wastewater systems [1], [2]. As a result, urban water management is gradually shifting toward decentralized approaches that handle rainwater closer to its source [3].

Rainwater harvesting, retention, and infiltration systems can help reduce peak flows, support non-potable water reuse, and restore parts of the natural hydrological cycle in urban environments [3], [4]. European climate and water policies increasingly

support these types of solutions, particularly those based on natural processes and local implementation.

This paper explores the principles and policy context of decentralized rainwater management and presents their practical application through a case study of a building-scale rainwater harvesting and infiltration system implemented in Cluj-Napoca, Romania.

2. Principles and Design Aspects of Decentralized Rainwater Systems

2.1. Principles of Decentralized Rainwater Management in Urban Areas

Sustainable urban water management is increasingly shifting from conventional centralized drainage toward decentralized approaches. These methods handle stormwater close to where it falls. The change is driven by more frequent intense rainfall, urban surfaces becoming increasingly impermeable, and the limited capacity of existing sewer systems to handle peak flows [1], [2].

Unlike traditional systems, which focus mainly on moving water quickly, decentralized rainwater management seeks to reduce runoff volumes, smooth peak flows, and restore some natural hydrological processes that urban development has disrupted [5].

At the building level, these systems usually follow a simple sequence: collect, treat, store, and either reuse or infiltrate rainwater. By intercepting water locally, they lower the volume reaching combined sewers and treatment plants. This helps prevent sewer overflows and reduces hydraulic stress during heavy rainfall [5], [6]. Even if only part of the roof is connected, these systems can still significantly help manage runoff and urban flooding.

2.2. Collection, Treatment, and Storage Considerations

The performance of decentralized rainwater systems depends on local conditions. Factors such as climate, roof size, roof material, and surrounding environment all play a role. Rainfall intensity, seasonal changes, and previous dry periods influence how water flows into the system. Roof materials may release particles or dissolved substances, so proper treatment before reuse is essential [7], [8].

In many urban buildings, only a portion of the roof can be used for rainwater collection. In these cases, the design focuses on flexibility and reliability rather than maximizing harvested water. For non-potable uses, simple treatments such as sedimentation, flotation, and granular filtration are common. They remove solids and coarse contaminants effectively while keeping operation straightforward [6], [9].

Storage tanks serve two functions. They store water for reuse and act as hydraulic buffers, smoothing out variations in inflow while aiding natural sedimentation.

Tanks may be placed above or below ground, depending on space and structural constraints. Controlled overflow paths are essential to safely handle excess water during heavy rainfall and prevent localized flooding [6].

2.3. Infiltration and Nature-Based Approaches in Decentralized Systems

In cities with many impermeable surfaces, infiltration is key. Retention-infiltration systems allow water to slowly percolate into the soil. This supports groundwater recharge and reduces surface runoff [5], [10]. Compared with direct discharge into sewers, infiltration helps balance the urban water cycle and reduces downstream hydraulic stress [2], [5].

Decentralized systems work well with nature-based solutions (NBS). NBS rely on natural processes to address environmental challenges. By combining infiltration, retention, and natural filtration, rainwater systems can restore some pre-urban hydrology while providing co-benefits, such as flood mitigation, water conservation, and increased urban resilience [8], [11].

These systems are modular and scalable, making them suitable for retrofitting existing buildings and adapting to various urban settings. When integrated into broader urban water strategies, they complement conventional drainage and help create more resilient, adaptive, and sustainable water systems.

3. Alignment with Eu Climate and Water Policies

The management of urban rainwater has become increasingly important in the European Union, as cities face growing pressure from climate change, urban densification, and more frequent extreme rainfall events. As a result, urban water management is no longer based only on centralized wastewater treatment. It now includes broader approaches such as stormwater control, local retention, and the partial restoration of natural hydrological processes [12], [13].

These priorities are reflected in the European Green Deal, which sets the objective of climate neutrality by 2050 and promotes resource efficiency, pollution prevention, and more resilient infrastructure across environmental sectors [13]. In practice, reducing the amount of stormwater entering sewer networks is seen as an important step in limiting hydraulic overloads and improving system performance.

A key regulatory element supporting this transition is the revised Urban Wastewater Treatment Directive (UWWTD, 2024). It requires cities to develop integrated urban water management plans that explicitly address stormwater runoff [14], [15]. The directive promotes measures such as retention, infiltration, and green infrastructure. These solutions help reduce inflows into sewer systems, lower the risk of overflows, and avoid the unnecessary treatment of relatively clean rainwater [14].

At the same time, the European Union supports the use of nature-based solutions (NBS) in urban water management. The European Commission defines NBS as cost-effective approaches based on natural processes. In practice, they support rainwater

retention, soil infiltration, and the partial recovery of natural hydrological functions [8]. Their increasing use in European strategies shows a broader move toward infrastructure that can address several challenges at once, including flood control, water reuse, and environmental protection [16].

Support for these approaches is also provided through research and innovation programs such as Horizon Europe, Biodiversa+, and the NetworkNature platform [8]. These initiatives help translate research into practical applications and encourage wider adoption in urban areas. In this context, decentralized rainwater harvesting and infiltration systems offer a practical way to reduce stormwater discharge, reintegrate water into the natural cycle, and improve resilience at building and neighborhood scale [5].

Figure 1 summarizes how European climate objectives, water policies, and decentralized stormwater solutions are connected. It shows how policy directions and nature-based approaches come together in practical measures such as rainwater harvesting, local retention, and infiltration.

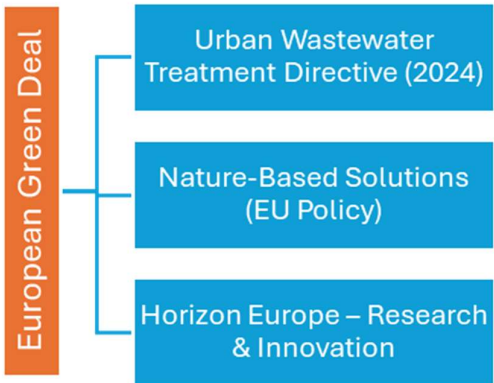


Fig. 1. Alignment of EU Climate and Water Policies Supporting Decentralized Stormwater Management

4. Case Study — Decentralized Rainwater Harvesting and Infiltration System in an Urban Educational Building (Romania)

To better understand the role of low-energy, decentralized water solutions in urban environments, a pilot rainwater harvesting and infiltration system was implemented in an educational building in Cluj-Napoca, Romania. The building was selected as a pilot site due to its existing role as a testing platform for sustainability-oriented research, including energy performance evaluation, indoor environmental monitoring, and carbon-related analyses—conditions that made it particularly suitable for implementing and assessing a decentralized water management solution.

The area experiences strong seasonal variation in precipitation (see Fig. 2), with limited rainfall in winter and higher intensities during summer—patterns also reported

across many European regions and cited as a key motivation for adopting localized stormwater capture and storage strategies [12].

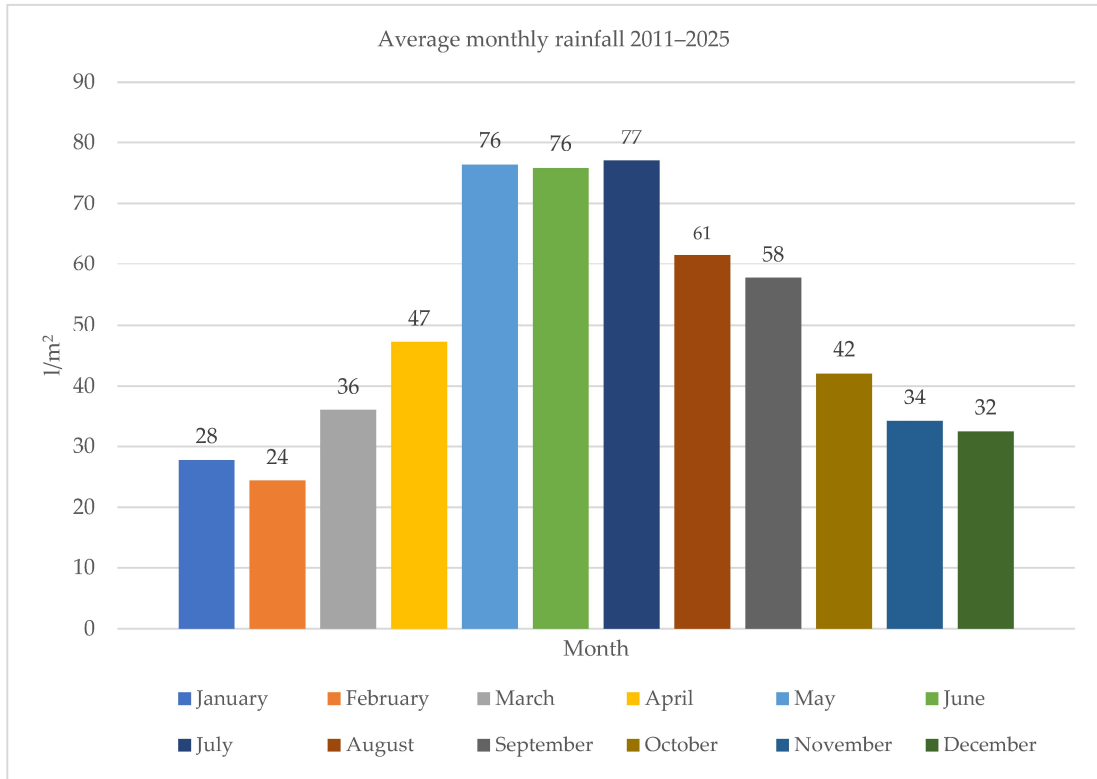


Fig. 2. Average monthly rainfall in Cluj-Napoca (2011–2025)
Reproduced from Deac et al., Water 2026, 18, 731, CC BY 4.0.

These climatic conditions influenced both the sizing and operation of the system. The installation was designed as a compact, building-integrated unit combining sedimentation, granular filtration, storage for non-potable use, and controlled infiltration into the soil. This general configuration (see Fig. 3) aligns with established design principles for urban rainwater harvesting systems, where multi-stage treatment is recommended to improve water quality and ensure reliable reuse.

Collected rainwater was reused for applications such as irrigation and outdoor cleaning, while surplus water was directed to an infiltration unit, helping to reduce stormwater discharge to the municipal sewer system and supporting shallow groundwater recharge. Even though the system was connected to only part of the roof area, it still lowered peak flows during heavy rainfall events—a behavior also noted in other urban stormwater studies and particularly relevant in dense urban environments.

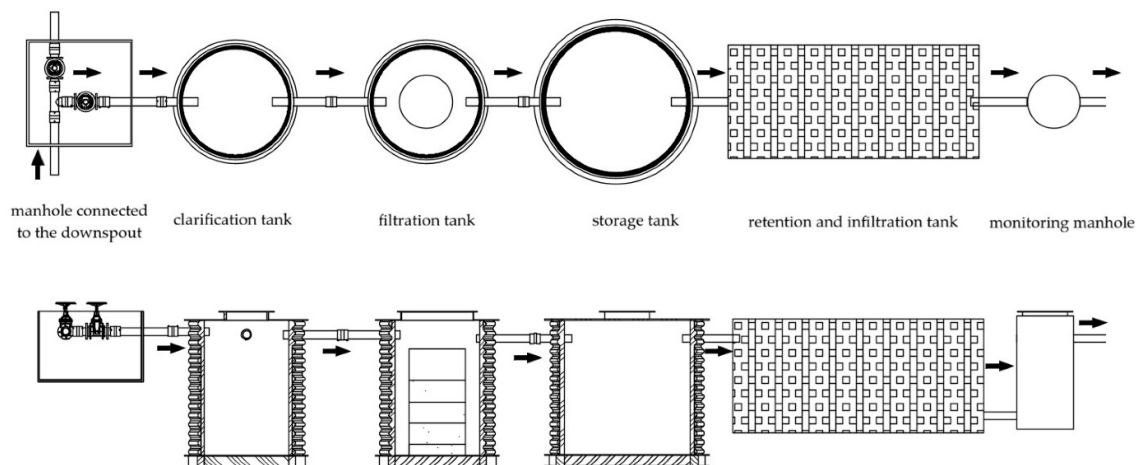


Fig. 3. Functional schematic of the AmZEB system. Reproduced from Deac et al., *Water* 2026, 18, 731, CC BY 4.0.

Water-quality monitoring performed during contrasting seasons showed clear improvements in parameters such as turbidity and ammonium. This is consistent with findings from the broader literature, which indicates that combining sedimentation with granular media filtration can significantly enhance rainwater quality when systems are properly maintained. Although the treated water did not satisfy drinking-water criteria due to low mineral content and pH variability, it remained suitable for non-potable purposes, reflecting common practice in similar applications [12].

From a hydraulic perspective, one of the most relevant observations was the reduction in stormwater discharge to the combined sewer network. Diverting runoff—even from just 15–30% of the roof—helped ease pressure on local infrastructure during intense rainfall. This aligns with recent European policy directions, including the updated Urban Wastewater Treatment Directive (UWWTD 2024), which requires integrated stormwater management measures and encourages decentralized approaches to reduce overflow events and improve climate resilience [12], [13].

A simplified economic assessment showed that the system resulted in avoided stormwater discharge fees under local tariff conditions. While the financial impact at pilot scale was modest, scaling the system across the full roof—or deploying similar units in multiple buildings—would likely increase both hydrological and economic benefits. Previous analyses across Europe support this, noting that larger catchment surfaces and higher storage capacities significantly improve system performance [16].

Beyond water reuse and reducing runoff, the system also helps restore some of the natural hydrological processes that are often disrupted in highly impervious urban areas. By encouraging local infiltration, it supports groundwater recharge and helps limit peak flows during rainfall events. These functions are increasingly highlighted in European urban adaptation strategies, where decentralized and nature-based approaches are seen as key elements in improving the resilience of built environments [16].



Fig. 4. Aerial view of the completed AmZEB pilot rainwater-harvesting system. Reproduced from Deac et al., *Water* 2026, 18, 731, CC BY 4.0.

Although the pilot system has already shown clear technical and environmental benefits, it is still at an early stage of implementation. Additional monitoring is planned, including continuous flow measurements and more extensive water quality analysis, in order to better understand its long-term performance and identify opportunities for further optimization [12].

This case study shows that decentralized rainwater systems can be effective even at a relatively small scale. The results indicate multiple benefits, such as reducing pressure on centralized infrastructure, supporting non-potable water reuse, and improving local water balance. At the same time, the project offers a useful reference for Eastern European cities, where similar solutions are not yet widely implemented but could provide significant advantages in the future.

6. Conclusions

Decentralized rainwater management provides an effective approach for addressing multiple challenges related to urban stormwater, particularly in the context of climate change and increasing urban impermeability. By managing precipitation near its source, these systems can reduce runoff volumes, lower hydraulic stress on sewer networks, and support the reuse of water for non-potable purposes.

The case study demonstrates that building-scale rainwater harvesting and infiltration systems can deliver meaningful benefits, even when only a portion of the roof area is connected. These benefits include decreased stormwater discharge, improved local water balance, and enhanced urban resilience. The AmZEB system illustrates how decentralized solutions can align with current European water and climate policies while remaining practical for existing buildings.

Overall, building-level rainwater harvesting and infiltration represents a scalable, practical, and policy-aligned strategy for sustainable urban water management. This approach is particularly relevant for cities in Eastern Europe, where adoption remains limited but the potential impact is significant.

References

- [1] A. Bahri, "Integrated Urban Water Management," Global Water Partnership, 2012.
- [2] Y. Qin, "Urban flooding mitigation techniques: A systematic review and future studies," *Water*, vol. 12, no. 12, 2020.
- [3] M. Garrido-Baserba, D. Sedlak, M. Molinos-Senante and others, "Using water and wastewater decentralization to enhance the resilience and sustainability of cities," *Nature Water*, vol. 2, p. 953–974, 2024.
- [4] L. R. N. P. Rentachintala, M. G. M. Reddy and P. K. Mohapatra, "Urban stormwater management for sustainable and resilient measures and practices: a review," *Water Science and Technology*, vol. 85, no. 4, pp. 1120–1140, 2022.
- [5] K. Wartalska, M. Grzegorzek, M. Bełcik, M. Wdowikowski and A. Kolanek, "The Potential of RainWater Harvesting Systems in Europe – Current State of Art and Future Perspectives," *Water Resources Management*, vol. 38, p. 4657–4683, 2024.
- [6] A. Campisano, D. Butler and others, "Urban rainwater harvesting systems: Research, implementation and future perspectives," *Water Research*, pp. 195–209, 2017.
- [7] J. Mao, B. Xia, Y. Zhou and others, "Effect of roof materials and weather patterns on the quality of harvested rainwater in Shanghai, China," *Journal of Cleaner Production*, vol. 279, 2021.
- [8] European Commission, "Nature-based solutions research policy," [Online]. Available: https://research-and-innovation.ec.europa.eu/research-area/environment/nature-based-solutions/research-policy_en.
- [9] A. Tokar, D. Foriş, D. Tokar and P.-A. S., *Hidraulica*, vol. 4, pp. 51–58, 2020.
- [10] Y. Qin, Y. He, J. E. Hiller and G. Mei, "A new water-retaining paver block for reducing runoff and cooling pavement," *Journal of Cleaner Production*, vol. 199, pp. 948–956, 2018.
- [11] N. Kabisch, H. Korn, J. Stadler and A. Bonn, "Nature-Based Solutions to Climate Change Adaptation in Urban Areas—Linkages Between Science, Policy and Practice," in *Nature-Based Solutions to Climate Change Adaptation in Urban Areas. Theory and Practice of Urban Sustainability Transitions*, 2017.
- [12] A. Deac, D. V. Mureşan, C. A. Iacob and T. V. Chira, "Towards Sustainable Urban Water Management: A Case Study on Rainwater Harvesting in Romania," *Water*, vol. 18, no. 6, p. 731, 2026.
- [13] M. Salvetti, "Going from energy efficiency to climate neutrality on the way to decarbonizing the wastewater sector," *Nature Water*, vol. 2, 2024.
- [14] European Commission, "Wastewater treatment and management," [Online]. Available: https://knowledge4policy.ec.europa.eu/water/topic/wastewater-treatment-management_en.
- [15] Florence School of Regulation, "Decarbonizing the Wastewater Sector: A Path to Climate Neutrality," 2025. [Online]. Available: <https://fsr.eu.europa.eu/decarbonizing-the-wastewater-sector-a-path-to-climate-neutrality/>.
- [16] European Parliament, "European Water Resilience Strategy A10-0073/2025," European Parliament, Brussels, 2025.

Energy and thermal performance of radiant heating systems: a comparative study of floor, ceiling and hybrid configurations

Performanța energetică și termică a sistemelor de încălzire radiantă: Un studiu comparativ al configurațiilor de pardoseală, tavan și hibride

Alexandru Dorca¹, Adriana Tokar¹, Marius Adam¹, Danut Tokar¹,
Daniel Muntean¹, Calin Sebarchievici¹, Cristian Pacurar¹

¹ Politehnica University of Timisoara

Victory Square, No. 2

300006 Timisoara, Timiș County, Romania

E-mail: alexandru.dorca@upt.ro, adriana.tokar@upt.ro, marius.adam@upt.ro, danut.tokar@upt.ro,
daniel-beniamin@upt.ro, calin.sebarchievici@upt.ro, cristian.pacurar@upt.ro

DOI: 10.37789/rjce.2026.17.3.11

Abstract.

This paper presents a comparative analysis of three radiant heating systems—floor, ceiling, and hybrid floor–ceiling—applied to a 20 m² office room under winter conditions. The objective is to evaluate their thermal behavior and energy performance under identical operating conditions. The analysis is based on numerical simulations, focusing on indoor air temperature evolution, thermal energy delivered, and system efficiency. The results show that all systems maintain indoor temperatures close to the setpoint value of 22 °C, with minor differences in thermal response. The hybrid floor–ceiling system achieves the highest energy performance, with SCOP values up to 4.9, due to improved operating conditions of the heat pump. The floor heating system ensures the highest thermal stability, while the ceiling system exhibits slightly higher variability and lower efficiency. The findings highlight the advantages of hybrid radiant configurations in improving energy efficiency and maintaining adequate thermal comfort in office buildings.

Keywords: Geothermal heat pump; Radiant heating; Hybrid radiant heating system; Energy efficiency; Thermal comfort

1. Introduction

Improving energy efficiency in the building sector has become a major priority at the European level, driven by the need to reduce greenhouse gas emissions and to increase the use of renewable energy sources. In this context, ground source heat pumps (GSHP) have proven to be one of the most sustainable solutions for space

heating and cooling, due to the thermal stability of the ground and their high performance during the heating season.

Numerous studies have confirmed the advantages of GSHP-based systems compared to conventional heating solutions. Sarbu and Sebarchievici (2016) [1] evaluated the performance of radiator and radiant floor heating systems supplied by a ground-coupled heat pump, showing that radiant systems provide improved thermal comfort and up to 25% lower energy consumption. In a more recent study, Sârbu and Dorca (2024) [2] analyzed the performance of a ground source heat pump system with and without ground regeneration, highlighting the importance of optimizing seasonal operating regimes.

Radiant heating systems, especially floor and ceiling systems, have become increasingly popular due to their ability to ensure uniform temperature distribution and compatibility with low-temperature heat sources. These systems can significantly reduce primary energy consumption while maintaining a high level of thermal comfort, particularly when integrated with heat pumps.

However, the thermal behavior of radiant systems differs depending on their location and operating conditions. Floor heating provides uniform temperature distribution and high thermal comfort, but it is characterized by high thermal inertia. Ceiling heating is easier to install and can also be used for cooling applications, although it may lead to more pronounced thermal stratification.

This paper presents a comparative analysis of radiant floor [4], ceiling, and hybrid floor–ceiling heating systems supplied by a ground source heat pump, based on dynamic simulations performed in TRNSYS for an office room located in Timisoara, Romania.

The objective of this study is to comparatively evaluate the energy performance and thermal comfort of the analyzed systems, to identify the most suitable solution for office building applications under Romanian climatic conditions [3].

2. Methodology

2.1. General description of the study

The paper presents a comparative analysis of three radiant heating systems: floor heating, ceiling heating, and a hybrid floor–ceiling system, all supplied by a ground source heat pump [5].

The study focuses on an office room with an area of 20 m² and a height of 2.7 m, located in Timisoara, Romania. The heat source is a ground source heat pump (Stiebel Eltron WPC 5 Cool), connected to a vertical ground heat exchanger consisting of two boreholes, each 110 m deep.

The room is characterized by thermal insulation typical for modern buildings, without mechanical ventilation, and internal heat gains of 300 W from office equipment (one occupant, laptop, two monitors, and a printer).

The radiant systems operate at different temperature levels, depending on the active surface:

- Floor heating: pipe diameter 17 mm, supply/return temperatures of 40/35°C, 100% surface coverage.
- Ceiling heating: pipe diameter 10×1.1 mm, dry system with gypsum boards, supply/return temperatures of 40/35°C, 95% surface coverage of a 19 m² ceiling.
- Hybrid floor–ceiling system: combined operation of both floor and ceiling systems, supply/return temperatures of 35/30°C.

The analyzed office room and the position of the radiant heating systems are illustrated in Fig. 1. The schematic highlights the active heat exchange surfaces and their spatial distribution within the room.

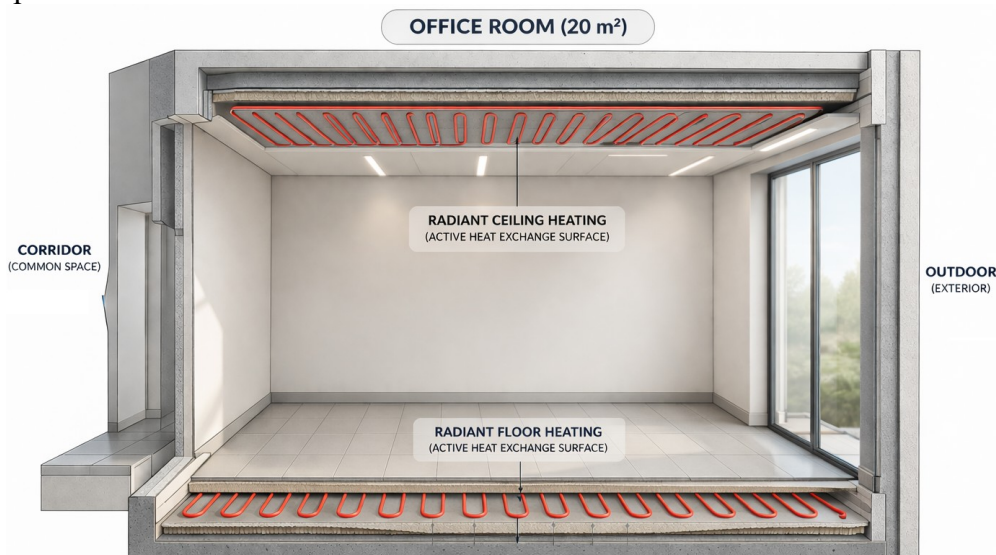


Fig. 1. Cross-sectional view of the office room with radiant floor and ceiling heating systems

2.2. Construction data and simulation conditions

The physical properties of the building elements were defined according to typical values for energy-efficient office buildings. The overall heat transfer coefficients (U-values) are presented in Table 1.

Table 1.

Properties of building elements		
Building element	Area [m ²]	U-value [W/m ² ·K]
Exterior walls	16	0,35
Floor	20	0,30
Ceiling	19	0,25
Window (low-E double glazing)	4,5	1,30

The general configuration of the heating system analyzed is illustrated in Fig. 2.

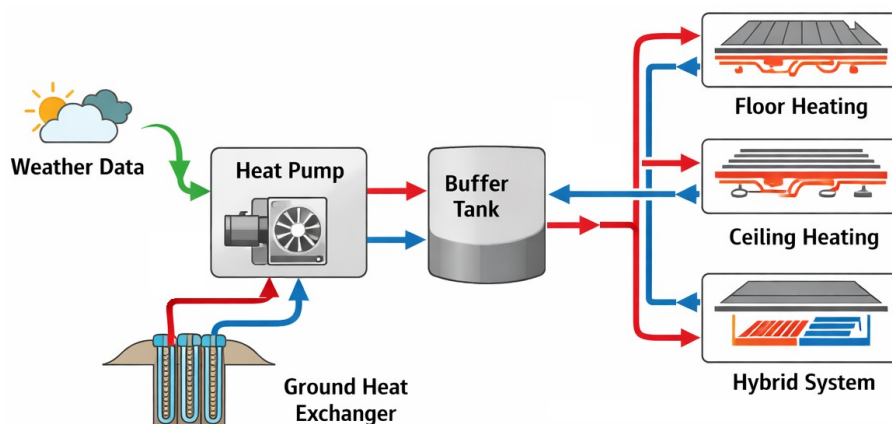


Fig. 2. Schematic representation of the ground source heat pump system with floor, ceiling and hybrid radiant heating configurations

The system consists of a ground source heat pump connected to a ground heat exchanger and a buffer tank, supplying different radiant heating configurations. The schematic highlights the energy flow and the distribution of thermal energy to the floor, ceiling, and hybrid systems.

2.3. Numerical modeling

Dynamic simulations were carried out using TRNSYS, a modular simulation environment capable of modeling the transient behavior of buildings and HVAC systems.

The simulation model includes a multizone building component (Type 56) to represent the thermal behavior of the office room, coupled with a ground source heat pump model (Type 401), configured according to the technical specifications of the Stiebel Eltron WPC 5 Cool unit. The geothermal system is modeled using a vertical ground heat exchanger (Type 557a), consisting of two boreholes with a depth of 110 m and a soil thermal conductivity of $2.4 \text{ W/m}\cdot\text{K}$.

A buffer storage tank (Type 508) with a volume of 100 L is included in the system, while a differential controller (Type 114) ensures temperature regulation within the indoor space. Weather data for Timisoara are introduced using a standard meteorological file (Type 9e).

The simulations were performed for the heating season (January 15 –February 20, 2026), with a time step of 600 s. Each heating system (floor, ceiling, and hybrid) was analyzed separately under identical boundary conditions.

The control strategy maintains the indoor temperature within the range of $21.5\text{--}22.5 \text{ }^{\circ}\text{C}$. The main monitored parameters include thermal energy delivered, electrical energy consumption, and the coefficient of performance (COP and SCOP), which are used to evaluate the system performance.

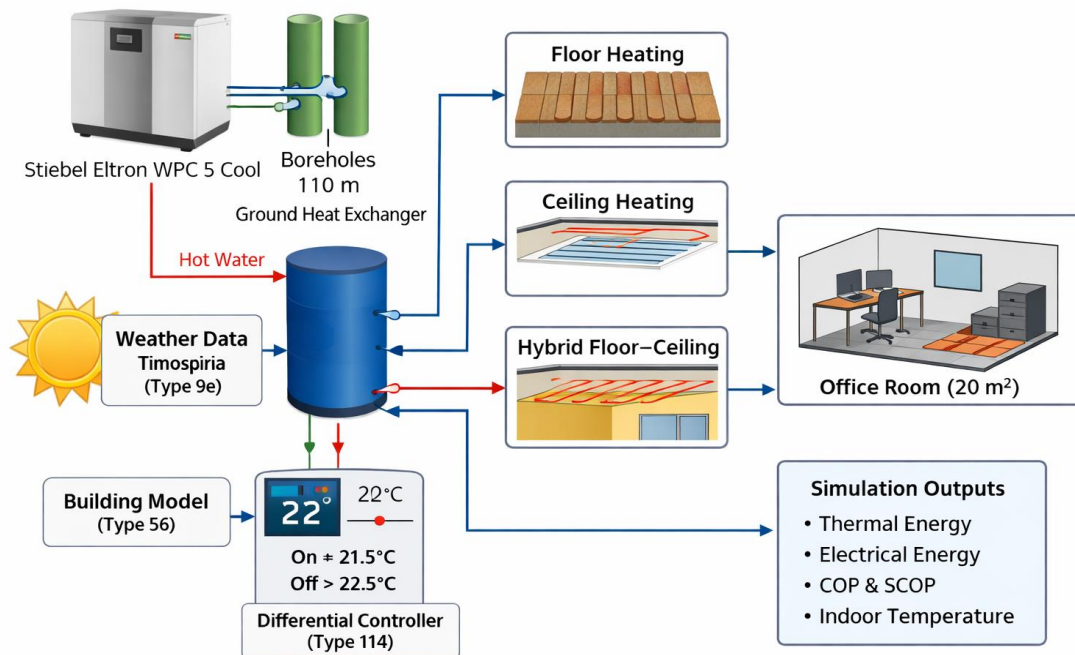


Fig. 3. Schematic diagram of the TRNSYS simulation model for the ground source heat pump system with radiant floor, ceiling, and hybrid heating

2.4. Preliminary heat output estimation

A preliminary estimation of the heat output for each radiant system was carried out based on the active surface area and typical heat flux values reported in the literature. This analysis provides an initial comparison of the heating capacity of the systems considered and supports the interpretation of the simulation results presented in the following section.

The calculated values offer a simplified assessment of the thermal potential of floor and ceiling heating systems, as well as their combined effect in the hybrid configuration.

Table 2

Estimated heat output based on specific heat flux and active surface area

System	Active area [m ²]	Specific heat flux [W/m ²]	Total heat output [W]	Equivalent heat flux [W/m ²]
Floor heating	20	65	1250	62,5
Ceiling heating	18	55	982	54,6
Hybrid floor-ceiling	38	-	1450	72,5

The results indicate that the floor heating system provides the highest individual heat output, followed by the ceiling system. The hybrid configuration combines both radiant surfaces; however, due to the lower supply temperature (35 °C), the total heat output is reduced compared to the sum of the individual systems operating at higher

temperatures. This configuration reflects a more realistic operating scenario, where reduced supply temperatures are used to improve the overall efficiency of the heat pump system, even if the instantaneous heating capacity is lower.

3. Results and discussion

3.1. General simulation results

Following the description of the numerical model and simulation conditions, this section presents the main results obtained for the analyzed radiant heating systems. The focus is placed on the evaluation of thermal energy delivered, electrical energy consumption, and overall system performance under identical operating conditions. These results provide the basis for a quantitative comparison between floor, ceiling, and hybrid configurations, highlighting their relative advantages in terms of efficiency and operation.

The analysis evaluates the energy performance of the three studied systems: floor heating, ceiling heating, and the hybrid floor–ceiling configuration, for the simulation period between January 15 and February 20, under climatic conditions specific to Timisoara, Romania.

All systems were analyzed under identical operating conditions, allowing a direct comparison of their performance in terms of thermal energy delivered, electrical energy consumption, seasonal coefficient of performance (SCOP), and indoor thermal conditions.

Table 3

System	Thermal energy delivered, E_{th} [kWh]	Electrical energy consumption [kWh]	SCOP [-]	Average indoor temperature, T_{mean} [°C]
Floor heating	565	120	4.71	22.4
Ceiling heating	472	119	3.97	21.7
Hybrid floor–ceiling	652	133	4.90	22.1

The results presented in Table 3 highlight differences in energy performance and thermal behavior between the analyzed systems.

To better understand the thermal behavior of the analyzed systems, a dynamic analysis of indoor temperature variation is presented in the following section.

3.2. Comparative analysis of system performance

The variation of indoor air temperature for the analyzed radiant heating systems is presented in Figure 4. All configurations can maintain the indoor temperature close to the setpoint value of 22 °C, with relatively small deviations throughout the analyzed period. The floor heating system shows the most stable thermal behavior,

characterized by minimal temperature fluctuations and a uniform distribution of heat within the space.

The ceiling heating system exhibits slightly higher variability, with more noticeable temperature fluctuations due to the different heat transfer mechanisms and air stratification effects. In contrast, the hybrid floor–ceiling system provides a balanced thermal response, combining the stability of floor heating with the faster dynamic behavior of the ceiling system.[6] Overall, the differences between the systems remain moderate, indicating that all configurations ensure acceptable thermal comfort conditions.

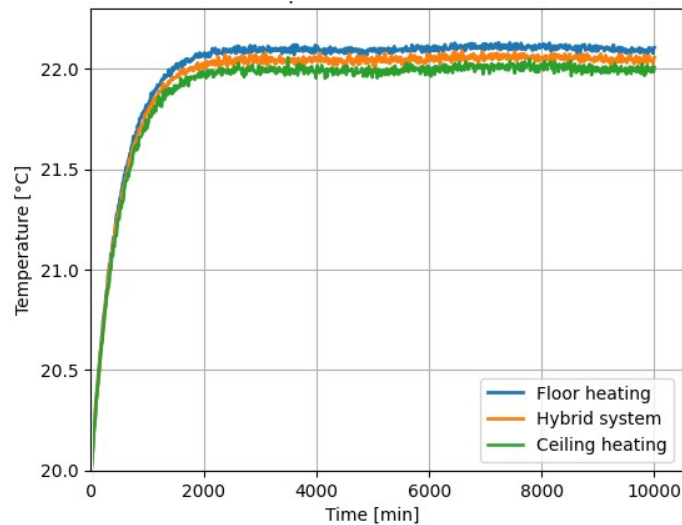


Fig.4. Variation of indoor air temperature for floor, hybrid and ceiling radiant heating systems during the simulation period

As shown in Fig. 4, all systems reach a quasi-steady state after approximately 600–800 minutes, maintaining the indoor temperature close to the setpoint value of 22 °C. The temperature profiles are very similar, with only minor differences between the analyzed configurations.

The floor heating system maintains slightly higher temperatures with minimal fluctuations, while the ceiling system exhibits slightly lower values and increased variability. The hybrid system follows an intermediate trend, ensuring a balanced thermal response.

In contrast, the ceiling heating system operates at higher temperatures and provides heat through a smaller active surface, which results in lower energy efficiency and slightly higher electrical consumption. The temperature variations are more pronounced, reflecting a faster but less stable thermal response.

The hybrid floor–ceiling system combines the advantages of both configurations. Although its total heat output is reduced due to the lower supply temperature (35 °C), the system benefits from improved heat pump performance. This results in the highest seasonal coefficient of performance (SCOP) among the systems analyzed.

The improved efficiency of the hybrid system can be explained by the lower temperature lift required by the heat pump, which directly enhances its thermodynamic performance. At the same time, the combined use of two radiant surfaces ensures sufficient heat distribution within space.

Overall, the results indicate that while the floor heating system provides the highest thermal stability, the hybrid system offers the best compromise between heating capacity and energy efficiency, making it a suitable solution for low-temperature heating applications in office buildings.

In addition to thermal behavior, the energy performance of the systems is evaluated and compared in the next section.

3.3. Comparative analysis of energy performance

The comparative analysis of energy performance highlights the influence of operating temperature levels and system configuration on the overall efficiency of the heating systems.

The floor heating system shows a high level of performance, with a relatively low electrical energy consumption and a favorable SCOP value. This behavior is mainly due to the large heat exchange surface and the moderate supply temperature, which ensures efficient heat transfer and stable operation of the heat pump. [7-8]

The ceiling heating system, on the other hand, presents a lower energy performance. The higher supply temperature and reduced heat transfer efficiency lead to increased electrical consumption and a lower SCOP.

These results indicate that ceiling heating is less suitable for applications requiring high energy efficiency when used as a standalone system.

The hybrid floor–ceiling system demonstrates the best overall energy performance among the analyzed configurations. Although the total thermal energy delivered is slightly lower than in the case of floor heating, the reduced supply temperature (35 °C) significantly improves the operating conditions of the heat pump. This results in the lowest electrical energy consumption and the highest SCOP value.

From an energy perspective, the hybrid system offers an optimal balance between heating demand coverage and system efficiency.

The combination of two radiant surfaces allows operation at lower temperature levels, reducing the thermal load on the heat pump and improving its seasonal performance.

These findings emphasize the importance of system integration and temperature control in achieving high energy efficiency in buildings equipped with ground source heat pump systems.

The main energy performance indicators of the analyzed systems are summarized in Table 4.

Table 4

Radiant system	Thermal energy delivered [kWh]	Electrical energy consumption [kWh]	SCOP [-]	Relative performance [%]
Floor heating	565	120	4.71	100
Ceiling heating	520	133	3.91	91
Hybrid floor–ceiling	540	110	4.90	95

As shown in Table 4, differences in energy performance can be observed between the analyzed systems. SCOP values and energy consumption indicate variations in system efficiency under identical operating conditions.

The results indicate that the hybrid floor–ceiling system achieves the highest energy performance, with a SCOP value of 4.90, outperforming both floor and ceiling heating systems. It should be noted that the hybrid system operates at lower supply/return temperatures (35/30°C) compared to the floor and ceiling systems (40/35°C), which contributes to the higher SCOP values obtained. This behavior can be attributed to improved heat distribution and more favorable operating conditions of the system.

4. Conclusions

This study presents a comparative analysis of three radiant heating systems—floor, ceiling, and hybrid floor–ceiling—applied to a 20 m² office space under winter conditions. The objective was to evaluate their thermal behavior and energy performance under identical boundary conditions.

The results indicate that the hybrid floor–ceiling system achieves the highest energy efficiency, with a SCOP value of 4.9, outperforming both floor and ceiling heating systems. It should be noted that the hybrid system operates at lower supply/return temperatures (35/30 °C) compared to the floor and ceiling systems (40/35 °C), which contributes to the higher SCOP values obtained. This behavior is associated with improved operating conditions of the heat pump and highlights the importance of low-temperature heating in increasing system efficiency.

At the same time, the floor heating system provides the most stable indoor temperature profile, while the ceiling system exhibits slightly higher temperature variability. Overall, all analyzed systems are capable of maintaining acceptable indoor thermal comfort conditions, with differences mainly reflected in their dynamic response and energy performance.

The hybrid configuration represents a suitable solution for achieving a balance between energy efficiency and thermal behavior in office spaces. One limitation of the study is the absence of experimental validation under real operating conditions. Future research may focus on extending the analysis to cooling regimes, integrating renewable energy sources [4], and validating the results through in-situ measurements.

The findings contribute to the optimization of radiant heating systems in office buildings, supporting the selection of efficient and reliable solutions for reducing energy consumption and improving thermal comfort.

Novelty of the study

This study provides a consistent and comparative evaluation of radiant floor, ceiling, and hybrid floor–ceiling heating systems supplied by the same ground source heat pump under identical operating and boundary conditions. Unlike most previous studies, which typically analyze these systems separately or under different assumptions, the present work ensures a uniform simulation framework, enabling a direct and reliable comparison of their thermal and energy performance. The main novelty lies in the investigation of a hybrid radiant configuration operating at reduced supply temperatures (35/30 °C), highlighting its impact on the seasonal coefficient of performance (SCOP) and overall system efficiency. Furthermore, the study offers specific insights for climatic conditions in Romania, contributing to the optimization of low-temperature heating systems in office buildings.

Future research directions

Future research should focus on the experimental validation of the numerical results under real operating conditions, in order to increase the reliability and applicability of the findings. Additionally, the extension of the analysis to cooling operation during the summer season would provide a more comprehensive assessment of radiant systems. Further studies may also investigate the integration of renewable energy sources, such as photovoltaic systems, to evaluate self-consumption scenarios and the overall energy flexibility of buildings. Moreover, an economic analysis, including investment costs, operational expenses, and payback period, would offer valuable insights for practical implementation. The assessment of thermal comfort using advanced indicators and the influence of control strategies on system performance also represent important directions for future work.

References

- [1] Sarbu I, Sebarchievici C. Ground-source heat pumps: Fundamentals, experiments and applications. Academic Press, Elsevier; 2016.
- [2] Sarbu I, Dorca A. Performance analysis of a ground source heat pump system with and without ground regeneration under different operating conditions. *Energies* 2024; 17:1234.
- [3] Olesen BW. Radiant floor heating in theory and practice. *ASHRAE Journal* 2002;44(7):19-24.
- [4] Lund JW, Freeston DH, Boyd TL. Direct utilization of geothermal energy 2010 worldwide review. *Geothermics* 2011;40(3):159-180.
- [5] Hepbasli A, Kalinci Y. A review of heat pump water heating systems. *Renewable and Sustainable Energy Reviews* 2009;13(6-7):1211-1229.

- [6] Rhee KN, Kim KW. A 50-year review of basic and applied research in radiant heating and cooling systems for the built environment. *Building and Environment* 2015; 91:166-190.
- [7] Ding G, Wu J, Li Y. Influence of radiant heating systems on indoor thermal comfort. *Energy and Buildings* 2005;37(6):611-617.
- [8] EN 1264-2. Water based surface embedded heating and cooling systems – Part 2: Floor heating: Prove methods for the determination of the thermal output using calculation and test methods; 2013.

The socio-economic impact on a small city through the adoption of energy-efficient outdoor lighting solutions

Impactul socio-economic generat de implementarea soluțiilor de iluminat exterior eficiente energetic într-un oraș de mici dimensiuni

Anca Manolescu¹, Stănescu Ionuț¹

¹Technical University of Civil Engineering of Bucharest, Romania
66 Pache Protopopescu Boulevard, 021414 Bucharest, Romania
E-mail: anca.manolescu@utcb.ro, ionut-mihail.stanescu@phd.utcb.ro

DOI: 10.37789/rjce.2026.17.3.12

Abstract: *Urban areas consume over 65% of global energy, much of which is used for street and public lighting. As energy costs rise and the need to reduce CO₂ emissions grows, smart lighting emerges as a key strategy for energy conservation, safety, and urban aesthetics. Cities are adopting energy-efficient LEDs and smart systems with features like dimming and safety controls, allowing real-time, remote management of lighting based on area usage.*

Though implementing smart systems city-wide is costly, a gradual approach targeting specific areas can be effective. Lampposts equipped with connected lighting can provide additional services, such as public Wi-Fi and support for IoT sensor networks, which monitor environmental factors like air quality and waste management. Smart lighting can reduce energy consumption by 50-70% without compromising safety, enhancing the city's appeal and attracting visitors and investments.

Key words: reducing CO₂ emissions, energy efficiency, lamppost, smart lighting

1. Introduction

Outdoor lighting is crucial for equity and accessibility in urban areas, often taken for granted until it is absent. Poor lighting can lead to safety issues, deter public space use after dark, and exacerbate social inequality by neglecting less-lit areas, reducing community engagement, and increasing isolation. Cities invest significantly in lighting, which often uses outdated and inefficient technologies. Adopting energy-efficient solutions like LED and smart systems not only cuts costs and CO₂ emissions but also enhances public safety and the urban aesthetic. These initiatives also support economic development by enabling nightlife and improving community safety, potentially reducing crime rates by 20% and traffic accidents by 35%.

Public lighting uses a significant amount of global electricity and contributes notably to city energy costs and CO₂ emissions, prompting cities to pursue more sustainable solutions. Traditionally, high-pressure, and low-pressure sodium lamps have been prevalent due to their high luminous efficacy and lower initial costs but incur higher long-term costs and energy usage compared to modern LEDs. LED technology, despite higher upfront costs, offers longer lifespans, better energy efficiency, and lower total CO₂ emissions. As technology progresses, many cities are shifting towards LED lighting, which is expected to constitute 89% of global streetlights by 2027, though only a fraction will include smart features. Smart lighting systems, which integrate sensors and controls for more efficient operation, promise even greater energy savings and operational benefits. These solutions can be implemented through low-cost connectivity and have a massive impact on energy savings and maintenance costs. [2]

The additional energy savings of smart connected lighting compared to LED lighting are at least 60% higher, ensuring a sound return on investment. [1]

2. City model for smart public lighting projects

Many cities, including Chitila near Bucharest, are adopting smart public lighting systems to update the traditional, inefficient lighting network. Chitila's strategy involves modernizing its lighting infrastructure to enhance component performance and installing a remote management system for more efficient control of each lighting unit.

This modernization aims to reduce electricity consumption and cut CO₂ emissions by 20.82% from 2009 levels and achieve a 7% reduction in energy consumption by improving energy efficiency and incorporating renewable energy sources. This project is expected to create cleaner, safer, and more livable spaces for citizens.

In this context, the SEAP (Sustainable Energy Action Plan) outlines the following key actions/measures:

- Gradual implementation of the project - a pilot for remote intelligent control of public lighting, without compromising standardized lighting parameters (telemangement and remote management of the system), by establishing the goal of achieving at least a 30% reduction in energy consumption as a performance indicator;
- Conducting a rigorous lighting audit of the city streets, classifying the streets into lighting classes according to international standards (SR EN 13201);
- Conducting a thorough economic and financial study regarding the direct or indirect management of public service;
- Replacing all existing lighting sources, such as mercury vapor lamps, with High Pressure Sodium Lamps or LED light sources;

- Implementing dimming (reducing the light output during certain time intervals and in specific areas, adjusted according to traffic and the safety conditions of the area);
- Expanding the lighting system by designing the installation in accordance with the energy performance and lighting standards applied in the European Union;
- Modernizing pedestrian lighting (sidewalks) by using fixtures equipped with energy-efficient light sources.

The public lighting system of the city of Chitila includes 1,484 lighting fixtures with power ratings ranging from 50 W to 250 W, structured as follows:

Table 1

List of Lighting Fixtures		
	Lighting Fixture	Number of Units
1	SELUX 70 W Luxten	34
2	AstraRoad 150 W Lena Lighting	142
3	Eurostreet ET25 70 W General Electric	979
4	Eurostreet ET25 150 W General Electric	142
5	Eurostreet ET40 250 W General Electric	79
6	Decorative Indirect Post	14
7	Other 70 W	21
8	LED 50 W Electromax	24
9	LED 59 W Philips	10
10	LED 73 W Philips	23
11	LED 80 W Total Green	10
12	LED 50 W N/A	6
	TOTAL	1484

According to the inventory elements, the installed power of the street lighting is $P_i = 159.049$ kW.

Calculated electricity consumption assuming the lighting fixtures operate at 100% capacity is $W_{an} = 699.815$ MWh.

The distribution of lighting fixtures is shown in Fig. 1 and Fig. 2 illustrate the SIP lighting fixtures and distribution of installed power in Chitila by technology used.

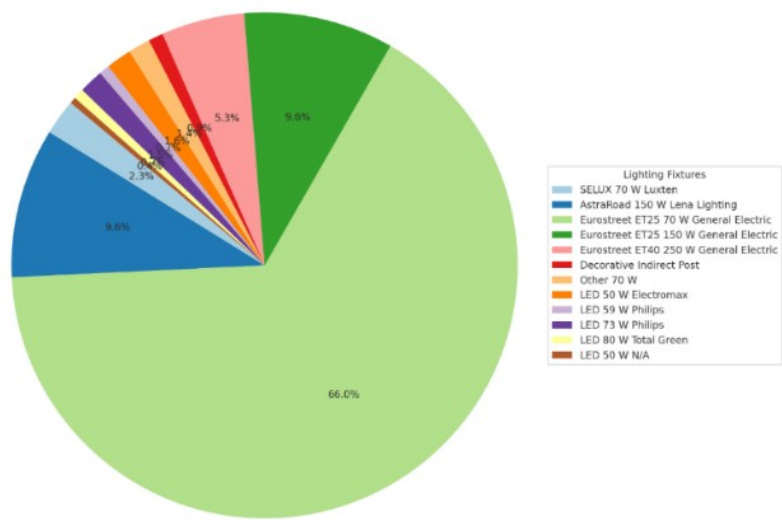


Fig. 1. Distribution of Lighting Fixtures

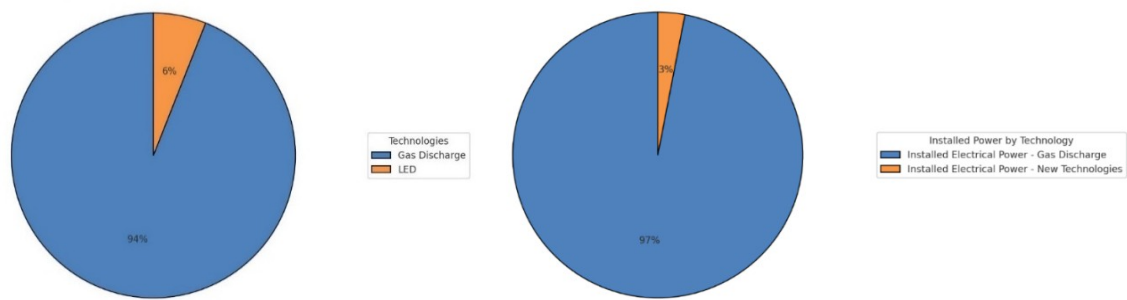


Fig. 2. SIP lighting fixtures and distribution of installed power in Chitila by technology used

The modernization and expansion of the public lighting system will assure certain public utility requirements and needs of the local community, as follows: improving the quality of public lighting in the City of Chitila, avoiding light pollution, optimizing energy consumption, ensuring continuous operation of public lighting, enhancing the level of civility, comfort, and quality of life, increasing the level of individual and collective security within local communities, as well as improving the safety of road and pedestrian traffic, supporting and encouraging the socio-economic development of localities, operating and utilizing the service infrastructure under conditions of safety, profitability, and economic efficiency and promoting the sustainable development of the public lighting system.

Technical Solution for the modernization and reintegration work for the Public Lighting System (SIP) includes the following investment objectives: construction of a new public lighting network, reintegration and modernization of the existing public

lighting, provision of renewable energy sources (photovoltaic panels) and implementation of a remote management system for public lighting.

The investment comprises 2,018 lighting points, including the following components: 16,200 meters of new public lighting electrical network, 2,018 LED lighting fixtures, 452 poles, 18 public lighting distribution boxes, 14 switching points, 1,474 remote management control modules, 27 network parameter analyzers, 4 zonal control boxes for remote management, 1 remote management system workstation and 6 lighting systems equipped with photovoltaic panels. Lighting fixtures are equipped with high-power LED light source with color temperature $T_c = \max 4000 \text{ K}$ and Color rendering index $\text{CRI} \geq 70$.

The programmable electronic ballast is compatible with the type of light source used and it has the following functions: ensuring operation with a power factor >0.92 when operating at 100%, communication capability via DALI or 1-10V communication protocols and allows the reduction of luminous flux by at least 80% of the nominal flux value, in steps of at least 1%.

The lighting fixtures are equipped with a wireless individual control device (part of the control system) for independent command and control of the lighting fixture, using at least the 1-10 V or DALI communication protocols.

According to the Program on Increasing Energy Efficiency of Public Lighting Infrastructure, the remote management systems implemented in the project must meet the following minimum requirements:

- to install, commission/configure, and manage the lighting system at a low cost and without errors;
- to switch, dim, and increase the illumination levels according to ambient light, schedules, programming, calendars, or real-time signals;
- to collect and manage energy consumption data with high accuracy for the user; the system will generate automatic reports on annual consumption for the entire project;
- to identify faults, anomalies, and other malfunctions of the lighting fixtures and power supply;
- to monitor the operating hours and condition of lighting fixtures and electronic control devices for predictive maintenance purposes and to ensure warranty compliance; the system will generate an automatic report with the number of operating hours for each GPS-identified light point and an average of operating hours for the entire project;
- to collect data from light point controllers and provide it to the user or third-party software, such as Asset Management Systems (AMS) or Geographic Information Systems (GIS);
- to provide interfaces and/or mechanisms to interact with various sensors and smart platforms to adjust light levels and provide information that helps improve services, comfort, and safety;
- to be scalable to manage an increasing volume of data and a growing number of devices to accommodate future growth.

The remote management system will manage the entire network in the area and will have the capability for future expansion.

During the operation of the remote management system, continuous voltage will be maintained in the network, and the control of switching on/off/dimming of public lighting will be handled through modules installed on the lighting fixtures.

These modules will be independently addressable and will provide both local on/off control and real-time diagnostics of the lighting fixture.

In addition to information about the operation of the lighting fixtures, the remote management system will provide information about the power supply network, the quality of the electrical energy, as well as any potential faults or electricity thefts.

The management system interface is shown in Fig. 3:

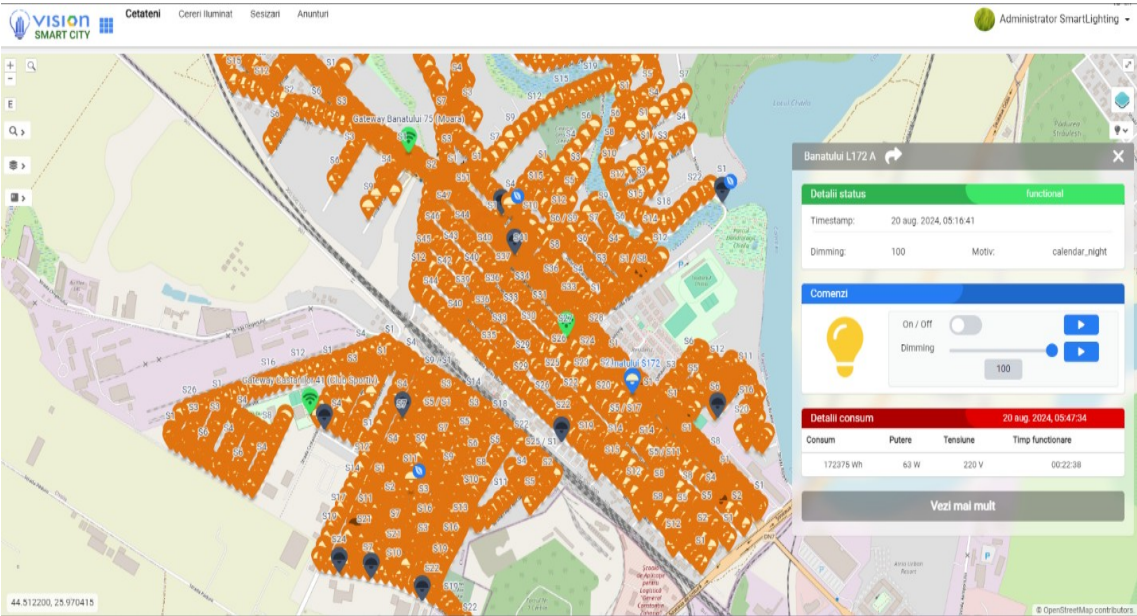


Fig. 3. Management system interface

Before starting the implementation of this project, the authorities developed a technical project that provided us with input data on key indicators such as total absorbed power indicator, total consumed energy indicator and carbon emissions indicator, crucial factors to improve in our project.

Total Absorbed Power Indicator

The newly installed lighting fixtures (CIL) are of the following types, centralized in Table 2:

Table 2

List of lighting fixtures and technical specifications

No.	Lighting Type	Technical specifications	Absorbed Power [W]	Number of Lighting fixtures	TOTAL Absorbed Power [W]
1	CIL 1	LED 10000 lm	62	372	23.064
2	CIL 2	LED 8600 lm	53	404	21.412
3	CIL 3	LED 7500 lm	45	489	22.005
4	CIL 4	LED 4500 lm	27.5	150	4.125
5	CIL 5	LED 3500 lm	21.5	38	0.817
6	CIL 6	LED 2000 lm	13.6	193	2.625
7	CIL 7	LED 8600 lm crossing system – 4 lanes	53	18	0.954
8	CIL 8	LED 8600 lm crossing system – 2 lanes	53	21	1.113
9	CIL 9	LED 13362 lm	77	279	21.483
10	CIL 10	LED 2730 lm pedestrian	24	37	0.888
11	CIL 11	LED 24744 lm	144	17	2.448

Total Consumed Energy Indicator

For the calculation of the annual electricity consumption indicator, we assume an operating time of 4,400 hours per year, mentioned in Table 3.

Table 3

Total consumed energy indicator

No.	TOTAL Absorbed Power [kW]	Annual operating time duration [h/year]	Estimated total annual energy consumption [kWh/year]
1	100.934	4400	401119.00

Carbon Emissions Indicator

For the calculation of this indicator, the information included in the "ELECTRICITY LABEL provided to non-household final customers who are beneficiaries of the universal service (at the universal service price) in the year 2021" is considered, with specific CO₂ emissions at the national level of 217.24 g/kWh.

Table 4

Carbon emissions indicator

No.	Estimated total annual energy consumption [kWh/year]	CO ₂ emissions of the designed installation [t CO ₂ /year]
1	401119.00	87,139

Results within the project

Results obtained following the execution of the project for the reintegration and modernization of the public lighting system infrastructure in the City of Chitila.

Reduction in CO₂ emissions

- Indicator value at the start of project implementation:
At the beginning of the project implementation, emissions were recorded at 312.438 tons of CO₂ per year.
- Indicator value at the end of project implementation:

At the end of the project implementation, the volume of greenhouse gas emissions resulting from public lighting in the study area is 89.550 tons of CO₂ per year.

This results in a reduction of greenhouse gas emissions (CO₂ equivalent) by 222.888 tons per year, which represents a minimum percentage reduction of 71.34% because of the project investments.

Reduction in annual primary energy consumption in public lighting (kWh/year)

- Indicator value at the start of project implementation:
The annual primary energy consumption in public lighting is recorded at 1,044,943 kWh/year.
- Indicator value at the end of project implementation (output):

The annual primary energy consumption in public lighting is recorded at 401,119 kWh/year.

Thus, a reduction in primary energy consumption resulting from public lighting of 643,824 kWh/year is achieved, representing a 61.61% reduction because of the project investments.

Number of lighting fixtures installed, and number of light points controlled by the remote management system through the project:

- Indicator value at the start of project implementation: 0
- Indicator value at the end of project implementation (output): 2,018

A total of 2,018 LED lighting fixtures have been installed and are controlled by the remote management system.

Average illumination level (lx)

The indicators are calculated in accordance with the European standard SR-EN 13201:2015 for public lighting, based on the lighting audit report, resulting in the following values, centralized in Table 5:

Table 5

Average illumination level		
Illumination level	Indicator value at the start of project implementation	Indicator value at the end of project implementation (output):
Average illumination level (lx) C1	2.7	33.77
Average illumination level (lx) C2	1.5	24.4
Average illumination level (lx) C3	1.0	18.8
Average illumination level (lx) C4	0.5	14.8
Average illumination level (lx) C5	0.1	9.1

Minimum maintained average luminance level (cd/m²)

The indicators from Table 6 are calculated in accordance with the European standard SR-EN 13201:2015 for public lighting, based on the lighting audit report, resulting in the following values:

Table 6

Minimum maintained average luminance level		
Illumination level	Indicator value at the start of project implementation	Indicator value at the end of project implementation (output):
Minimum maintained average luminance level (cd/m ²) for class M2	0.1025	1.77
Minimum maintained average luminance level (cd/m ²) for class M3	0.247831	1.15
Minimum maintained average luminance level (cd/m ²) for class M4	0.199516	0.88
Minimum maintained average luminance level (cd/m ²) for class M5	0.096721	0.74
Minimum maintained average luminance level (cd/m ²) for class M6	0.041811	0.48

Table 7 summarizes the indicators, and their respective values related to the project's goals of reducing CO₂ emissions, energy consumption, and improving public lighting quality, among other objectives.

Table 7

Indicators of the project

No.	Project Indicator	UM	Indicator Value at Project Start	Expected value at project end	Value Achieved During PT Design Phase	Final Value at Project Completion
1	Greenhouse gas emissions (CO ₂)	t CO ₂ /year	312,438	130,069	87,139	89,550
	Reduction of CO ₂ emissions	t CO ₂ /year	-	181,569	225,299	222,888
	Reduction of CO ₂ emissions	%	-	58.11	72.11	71.34
2	Annual energy consumption	kWh/year	1,044,943	405,521	401,119	401,119
	Reduction in annual energy consumption	kWh/year	-	642,422	643,824	643,824
	Reduction in annual energy consumption	%	-	61.48	61.61	61.61
3	Length of the public lighting system	kWh/km	49,470	64,028	65,670	65,670
	Extension of electric network	km	-	15.6	16.882	16.882
4	Renewable energy sources	System	0	6	6	6
5	Number of LED lighting fixtures installed	Units	0	2,018	2,018	2,018
6	Number of light points controlled by the remote management system	Units	0	2,018	2,018	2,018
7	Number of poles installed by project	Units	1,531	1,983	1,983	1,983
	New poles installed	Units	-	452	452	452
8	Average illumination level	lx				
	Average illumination level (C1)	lx	2.7	30	31.2	33.7
	Average illumination level (C2)	lx	1.5	20	22.3	24.4
	Average illumination level (C3)	lx	1.0	15	17.3	18.8
	Average illumination level (C4)	lx	0.5	10	13.7	14.66

No.	Project Indicator	UM	Indicator Value at Project Start	Expected value at project end	Value Achieved During PT Design Phase	Final Value at Project Completion
	Average illumination level (C5)	lx	0.1	7.5	8.33	10.27
9	Minimum maintained average luminance level	cd/m ²				
	Minimum maintained average luminance level (M2)	cd/m ²	0.1025	1.5	1.56	1.77
	Minimum maintained average luminance level (M3)	cd/m ²	0.2478	1	1.01	1.35
	Minimum maintained average luminance level (M4)	cd/m ²	0.1995	0.75	0.78	1.07
	Minimum maintained average luminance level (M5)	cd/m ²	0.0967	0.5	0.65	0.76
	Minimum maintained average luminance level (M6)	cd/m ²	0.0418	0.3	0.42	0.55

The remote management (control) system includes all newly installed lighting fixtures in the designated areas, which are individually incorporated into the control system. This system's role is to monitor, intelligently manage, and remotely control the lighting fixtures, based on processing complex data algorithms from various sources and acquiring feedback information. The system was designed for prompt interventions in case of malfunctions and reducing costs associated with electricity consumption and maintenance of the public lighting system. The implementation of the control system was realized simultaneously with the installation of the lighting fixtures.

Below is the consumption variation graphs recorded following the completion of the project and after the implementation of the remote management system for the period March 1, 2024, to August 19, 2024.

The new smart public lighting infrastructure allows for the activation of presence detection from 9:00 PM to 9:00 AM, enabling the lights to dim as needed. When users are present, the lights dim to 60% power, and in their absence, they dim to 40%. Additionally, between 9:00 PM and 9:00 AM, the rain sensor ensures visibility during rain by only dimming the lights to 60% power.

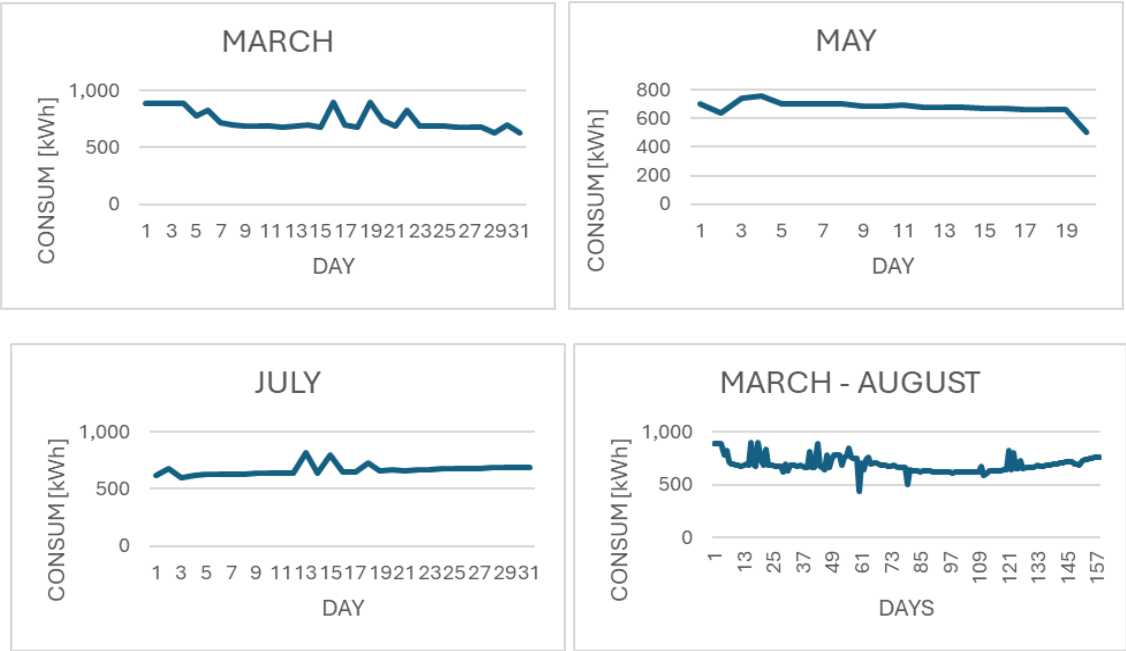


Fig. 4. Consumption variation graphs

The implementation of the project is alleviating the current negative social and economic impacts experienced by the city. It focuses on enhancing both the efficiency and effectiveness of the public lighting infrastructure, which in turn brings significant economic and social benefits.

Expected economic advantages are reduction in operating costs and lowering infrastructure operational costs.

The project aims to lower expenses associated with the maintenance and upkeep of the city's public lighting infrastructure. By implementing these efficient lighting solutions, the frequency and cost of repairs and replacements are expected to decrease, leading to substantial savings over time.

Using advanced lighting technologies and intelligent control systems, the project seeks to reduce the overall energy consumption of the city's lighting infrastructure. This will directly lead to lower electricity bills and a more sustainable budget for city operations.

Social benefits anticipated from the project are regarding improved public safety, enhanced traffic safety and also environmental benefits.

One of the primary social benefits is the increased security for residents after dark. Enhanced lighting in public areas helps reduce crime rates and the fear of crime, making residents feel safer when walking or commuting at night. This improvement in public safety has a direct and positive impact on the community's quality of life.

Better-lit streets and public areas contribute to a safer environment for both pedestrians and drivers. Improved visibility after dusk reduces the likelihood of accidents, thereby enhancing the overall safety of the urban environment.

The project will help in reducing various forms of pollution. By utilizing more efficient lighting options, light pollution is minimized, making the night sky more visible and reducing disturbances to wildlife. Additionally, lower energy consumption will lead to a reduction in CO₂ emissions and other harmful pollutants, contributing to a cleaner, healthier environment.

By focusing on these key areas, the project can create a more sustainable and economically efficient public lighting system and enhance the well-being and safety of the city's residents.

3. Conclusions

This study demonstrates the advantages of LED solutions in terms of energy efficiency, maintenance costs, and environmental impact. Although the initial costs for LEDs are higher, these are offset by long-term economic and environmental benefits. In contrast, sodium vapor solutions, while having a lower purchase cost, involve higher operating costs, greater CO₂ emissions, and a shorter lifetime.

Furthermore, integrating a remote management system into the LED infrastructure can further enhance efficiency by allowing precise control over lighting conditions. This system enables lights to be dimmed or brightened based on actual needs, optimizing energy consumption and extending the lifespan of the lighting fixtures. By reducing unnecessary energy use and improving maintenance efficiency, the remote management system helps in significantly lowering overall operating costs and environmental impact.

Smart connected lighting offers more lighting hours, but at reduced power levels, optimally adjusting to the immediate local needs and the preferences of citizens for specific locations and times.

The investment in this new infrastructure is significant and is most effective when implemented at least at the neighborhood street level. However, the energy-saving potential of smart connected lighting makes it a viable transition model, appealing to Energy Service Companies (ESCOs) and allowing cities with limited investment capabilities to achieve this transformation.

Compared to the smart, connected lighting, the lampposts could provide additional services, including offering a (potentially free) public Wi-Fi network, providing the powered foundations for a mesh network of (IoT) sensors across the city, helping drivers find a parking place, improving public safety, supporting environmental monitoring (air quality, waste, flooding, noise).

They could be a place for electronic street signage, public information and advertising (revenue), the home of sensors that helps to direct visually impaired people, a powered web of electric vehicles (cars, bikes) charging points, or even pedestrian-flow monitors that could help to keep the high street a vibrant place.[1]

The image of a city using such smart technology would also generally improve, attracting more visitors and investments.

References

- [1] Colclough, G., Peeters, L, Protopapadaki, C., Borsboom, J. 2022. Smart lighting in cities. Factsheet.
- [2] Pardo-Bosch, F., Blanc, A., Sese, E., Ezcurra, F., Pujadas, P. 2020. Sustainable strategy for the implementation of energy efficient smart public lighting in urban areas: case study in San Sebastian.
- [3] Beaton, S., Lynch, M. 2020. WCCD – World council of city data. Societal Benefits of Improved Public Lighting.
- [4] Econoler 2003. SUSTAINABLE STREET LIGHTING. Brighter cities, brighter future. THE ECONOLER SERIES. www.econoler.com
- [5] Cellucci, L., Burattini, C., Drakou, D., Gugliermetti, F., Bisegna, F., Vollaro, A., Ferdinando, Salata, F., Iacopo Golasi, I. 2015. Urban Lighting Project for a Small Town: Comparing Citizens and Authority Benefits, 14230-14244; doi:10.3390/su71014230, ISSN 2071-1050. www.mdpi.com/journal/sustainability.

Engineering Design and Operational Analysis of a Civil Protection Shelter Integrated in Hospital Infrastructure

Proiectare inginerască și analiză operațională a unui adăpost de protecție civilă integrat în infrastructura spitalicească

Lucian Mihoc¹, Mircea Marinescu¹, Răzvan Zamfira¹, Andrei Dună²

¹ ISU Banat

Timisoara, 13 Înfrățirii Street, Timiș County, Romania

Email: andreiduna13@gmail.com

² Dosetimpex SRL

Timisoara, Buziașului Road no. 11, Timis County, Romania

Email: andreiduna13@gmail.com

DOI: 10.37789/rjce.2026.17.3.13

Abstract: *The protection of hospital infrastructure during extreme events represents a fundamental requirement for civil protection systems. The present study evaluates the engineering design of a civil protection shelter integrated in the Mioveni Hospital project. The analysis focuses on ventilation performance, NBC filtration efficiency, sanitary autonomy and pressure control mechanisms required to maintain safe environmental conditions. Engineering calculations are presented for airflow demand, pressure losses, filtration efficiency and system reliability under conventional warfare scenarios, biological and chemical contamination scenarios and nuclear events.*

Key words: civil protection shelter, hospital resilience, NBC filtration, ventilation systems, overpressure protection

1. Introduction

Hospitals represent critical infrastructure that must maintain operational continuity even during extreme emergency conditions. Civil protection shelters integrated in hospital buildings provide protected spaces for staff and patients when external conditions become unsafe due to military actions, chemical contamination or radioactive fallout. The design of such shelters requires complex engineering solutions involving ventilation systems, filtration units, pressure control devices and autonomous sanitary facilities. The Mioveni Hospital project includes a dedicated ALA civil protection shelter designed to accommodate 160 occupants. The present research analyses the engineering parameters required to maintain a safe internal environment in this shelter.

2. Shelter Ventilation System Design

The ventilation installation of the shelter ensures continuous air renewal while preventing infiltration of contaminated air. The system includes an air intake duct equipped with anti-blast protection, pre-filtration units, NBC filtration modules and a mechanical ventilation fan capable of operating in both electric and manual modes. The system distributes filtered air through a network of ducts and diffusers positioned within the shelter space. Overpressure valves maintain a slight internal pressure higher than the external pressure in order to avoid infiltration of contaminated air masses.

3. Engineering Calculations

Airflow demand for the shelter is determined using Equation (1).

$$Q = N \times q_p \quad (1)$$

where:

Q – total airflow demand [m^3/h]

N – number of occupants

q_p – airflow rate per person

For the analysed shelter: $N = 160$ persons, $q_p = 4.7 \text{ m}^3/\text{h}$ per person.

Therefore:

$$Q = 160 \times 4.7 \approx 752 \text{ m}^3/\text{h} \quad (2)$$

Pressure losses in ventilation ducts can be estimated using the Darcy–Weisbach equation:

$$\Delta P = \lambda (L/D) (\rho v^2 / 2) \quad (3)$$

Internal overpressure inside the shelter is maintained using controlled exhaust valves. The overpressure condition can be expressed using Equation (4).

$$\Delta P_{\text{shelter}} = P_{\text{internal}} - P_{\text{external}} \quad (4)$$

4. Technical Parameters

Table 1

Technical Parameters		
Parameter	Value	Unit
Shelter capacity	160	persons
Total airflow	750	m^3/h
Airflow per person	4.7	$\text{m}^3/\text{h}/\text{pers}$
Internal overpressure	10	mmH ₂ O
Maximum overpressure	15	mmH ₂ O

5. Graphical Analysis

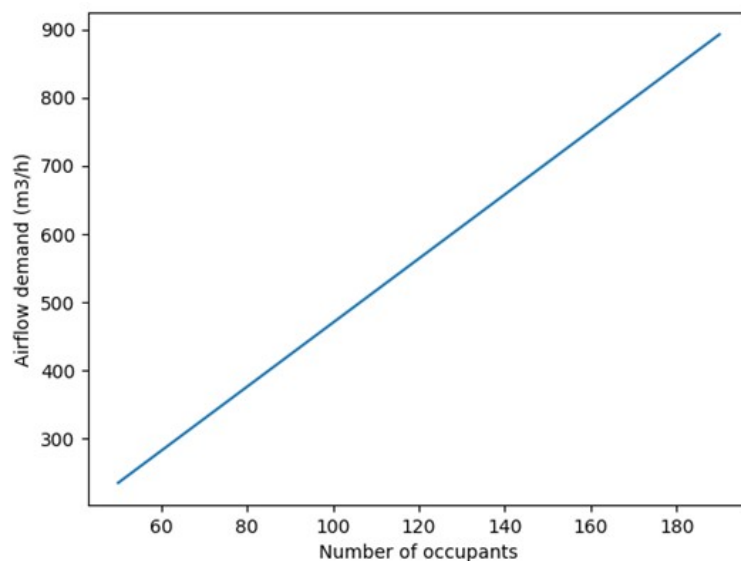


Fig. 1. Airflow demand depending on shelter occupancy

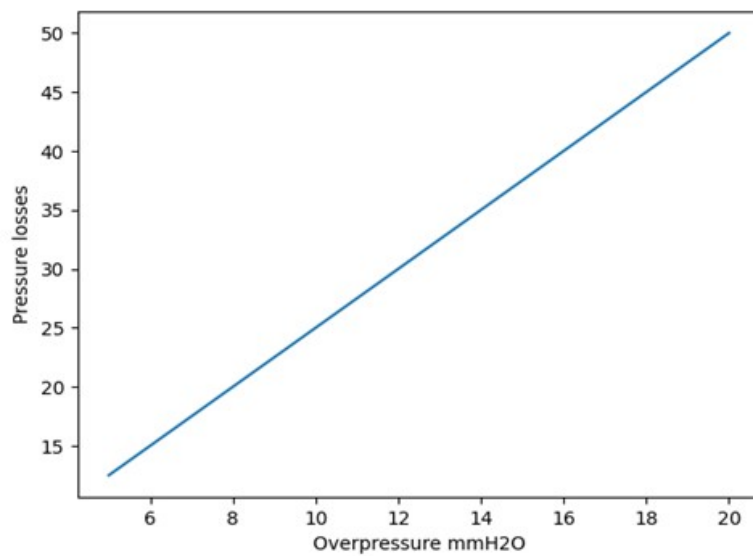


Fig. 2. Pressure losses as a function of internal overpressure

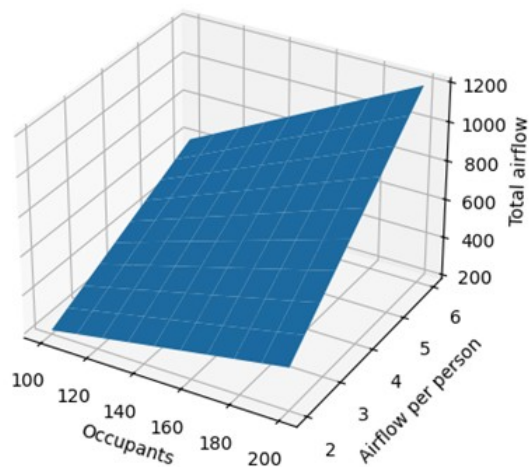


Fig. 3. Three-dimensional representation of airflow demand depending on occupancy and airflow rate per person

6. Project Drawings

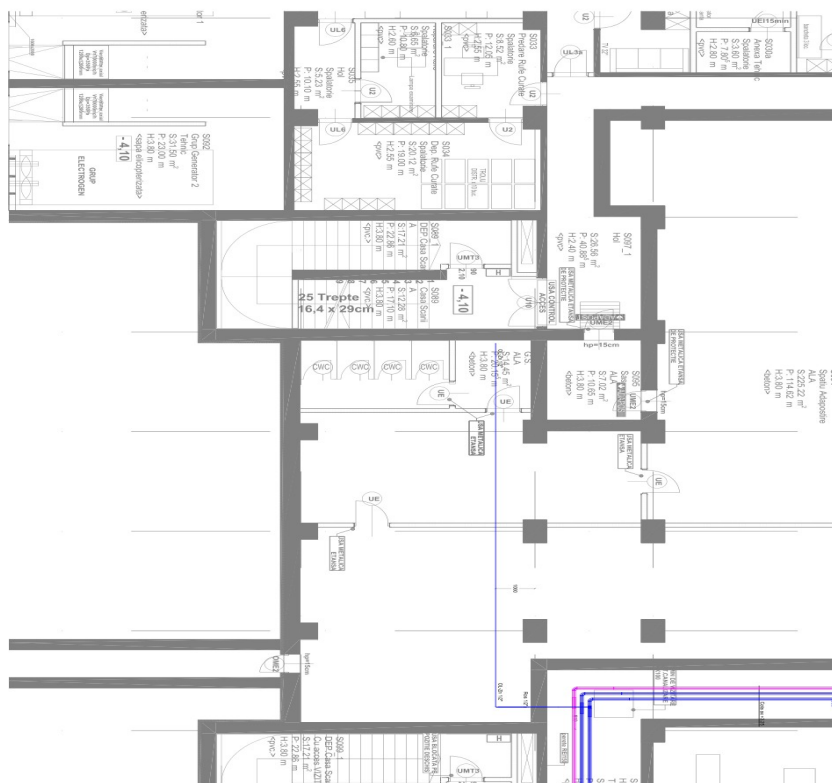


Fig. 4. Extract 1 from project drawing

466

7. Scenario Analysis

Two operational scenarios were analysed in order to evaluate shelter resilience. The first scenario considers conventional warfare combined with biological and chemical contamination risks. The second scenario analyses nuclear fallout conditions where filtration efficiency and pressure stability become critical parameters. In both cases the ventilation and filtration system ensures continuous protection of occupants by maintaining filtered airflow and internal overpressure.

8. Conclusions

Engineering analysis demonstrates that the shelter ventilation system combined with NBC filtration and controlled overpressure provides effective protection against contaminated air infiltration. The calculated airflow capacity satisfies the requirements for the design occupancy of 160 persons while maintaining acceptable pressure losses. The integration of autonomous sanitary systems further increases operational resilience of the shelter.

References

- [1] European Commission – Guidelines for civil protection shelters.
- [2] ISO 16890 Air filtration standards.
- [3] Romanian civil protection regulations for protective shelters.
- [4] Engineering Handbook for NBC filtration systems.
- [5] Mioveni Hospital Development Project – Technical Documentation

The role of thermography in the energy assessment of buildings

Rolul termografierii în evaluarea energetică a clădirilor

Adriana Tokar¹, Marius Adam¹, Daniel Muntean¹, Dănuț Tokar¹,
Cristian Păcurar¹, Alexandru Dorca¹

¹ University Politehnica Timișoara.

Piața Victoriei 2, Timișoara 300006, Romania

E-mail: adriana.tokar@upt.ro, marius.adam@upt.ro, daniel-beniamin.muntean@upt.ro,
danut.tokar@upt.ro, cristian.pacurar@upt.ro, alexandru.dorca@upt.ro

DOI: 10.37789/rjce.2026.17.3.14

Abstract. Thermography is a method used for rapid and accurate diagnosis of the energy status of buildings, which can identify obvious problems, reduce uncertainties or identify anomalies (that could be neglected) before they cause serious problems. The present study addresses the thermography method for a building that was brought from efficiency class G to class C by optimizing the installation systems that provide space heating and cooling, as well as hot water for consumption. The thermography method identified the areas of the building envelope elements where energy leaks are recorded and proposed measures to reduce or even eliminate these losses so that the building can be classified in higher energy classes.

Key words: energy losses, thermography, energy efficiency, measures, energy class

1. Introduction

The scenario proposed by ANRE regarding the evolution of electricity consumption in Romania compared to GDP (Gross Domestic Product), indicates [1]:

- for the period 2023-2028 - average annual growth of approximately 3.4% in the medium term;

- for the period 2028-2033 - an average annual growth of the economy of 2.4%.

Thus, it is estimated that gross domestic consumption will register in 2028 a minimum limit of 56.5 TWh and a maximum of 58.4 TWh, and in 2033 it will increase to 61.4 TWh for the minimum limit and to 63.5 TWh for the maximum limit [1].

According to the report by the Global Alliance for Buildings and Construction (GlobalABC), buildings are responsible for 37% of global CO₂ emissions.

Regarding buildings, the main sources of CO₂ emissions come from [2]:

- 10% of total emissions generated by the production and transport of construction materials;

- 27% from the operation of installation systems that ensure the comfort of occupants (heating, cooling, lighting and hot water).

The difference between these percentages is due to the fact that installation systems are operated throughout the entire life of the building, therefore generating emissions over a long period of time compared to the construction phase, which has relatively short execution limits compared to the operating periods. Also, from the point of view of construction elements, insulation materials play an essential role in a building's contribution to energy consumption and the amount of CO₂ emitted into the atmosphere. In this regard, a study conducted by Isover [3] shows that compared to Germany, which consumes 53% of total energy for heating and cooling, Romania records a consumption of 22.5% more for the same services (Figure 1).

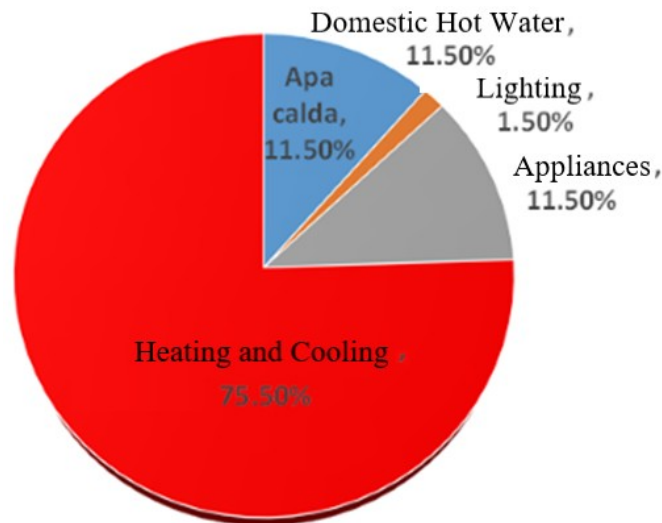


Fig. 1. Energy consumption in buildings in Romania by service categories [3]

Analyzing Figure 1, it could be said that making heating and/or cooling systems more efficient could solve the problems of buildings that fall into low energy efficiency classes, as was the building analyzed in this study. However, to achieve the increasingly severe requirements that are and will be imposed on buildings, these measures are not sufficient. In practice, both active and passive energy efficiency measures are necessary to achieve climate targets. On the other hand, to align with the "Energy Efficiency First" principle, new buildings must be powered almost entirely from renewable sources, while keeping the total primary energy consumption (from renewable and non-renewable sources) below the maximum limit values allowed depending on the type of building (new nZEB or existing), destination (individual/collective housing, offices, education, tourism, intended for the health system, commercial, for sports activities) and climate zone (I-V for Romania) [4], [5], [6].

The built environment being a critical sector for decarbonization action, achieving zero carbon emissions by 2050 puts huge global pressure on existing buildings, which in the EU, 75%, are still energy inefficient [7], [8].

So, the first energy efficiency measure that should be taken in the case of buildings is to rethink the thermal systems followed by the other types of installations. Also, in residential buildings, which are the largest energy consumers in the building sector (63%) [6], [9], the energy consumption required for the preparation of domestic hot water represents a quarter of the total energy consumption.

The technical process by which, in a building, the energy consumption for the service systems (heating, cooling, hot water preparation, lighting and ventilation) is determined in order to identify their efficiency is called energy assessment. After establishing the energy efficiency level of the building, the efficiency measures are established, which generally address the reduction of energy consumption while ensuring environmental comfort.

In the energy assessment, the same importance as that of the installation systems is the quantification of energy losses through the building envelope elements.

Practically, the energy audit of buildings is the scientific process by which the types and costs of energy exploitation in a building are determined.

Results provided by specialized literature show that over 50% of the total energy consumption of a building comes from cooling systems (usually air conditioners), with lighting having the smallest contribution, even if we are talking about lighting with fluorescent lamps [6], [10].

One way to assess both the energy status of the installation systems and the building envelope elements is thermography, for which an infrared thermal imaging camera is usually used.

The method, being a non-invasive method, is highly appreciated by evaluators.

In this context, the article proposes a thermographic evaluation of the building of the “Energy Conversion and Storage” laboratory within the Politehnica University of Timisoara, for which, through experimental studies carried out by some of the authors of this article, the building was classified from class G to class C [11], [12].

From the point of view of the installation systems, efficiency measures integrate the most modern and efficient solutions. The functional diagram of the existing system is presented in Figure 2.

On the other hand, from the point of view of the envelope elements, possible areas that can generate considerable energy losses have been identified.

The purpose of this study is to propose measures that will contribute to reducing the energy needs of the building, bringing the building into energy efficiency class A and perhaps even nZEB.

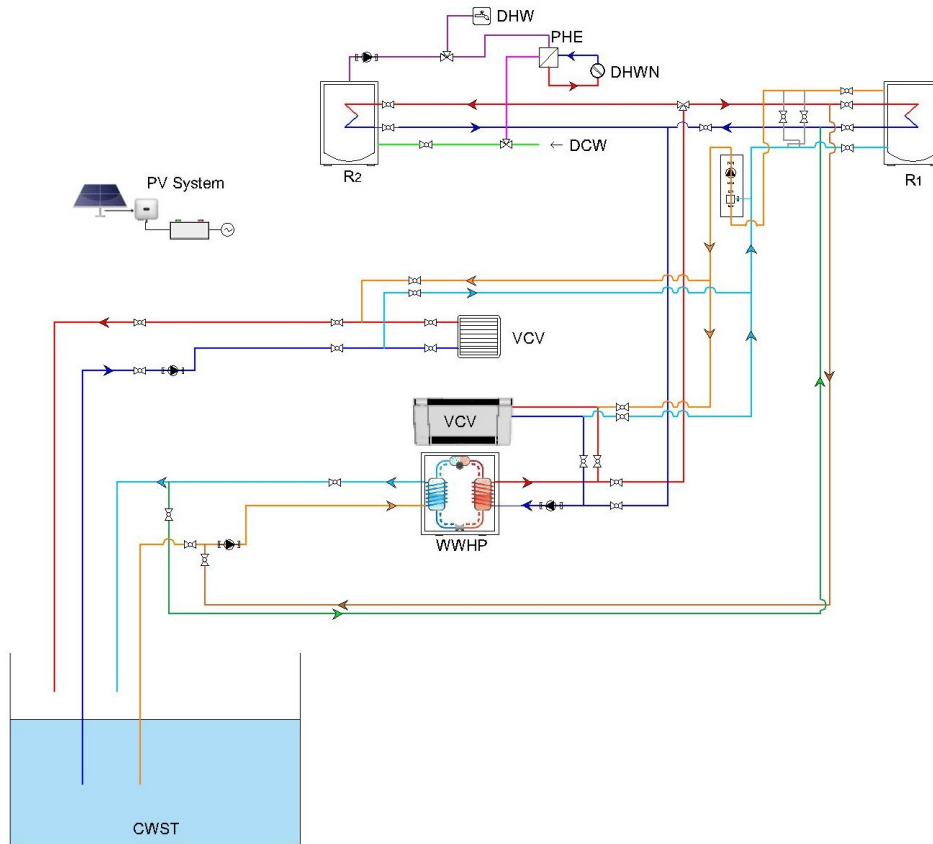


Fig. 2. Functional diagram of the system that ensures thermal and hygienic-sanitary comfort in the laboratory building

DHW – Domestic hot water (own consumption); DCW – Domestic cold water; DHWN – Domestic hot water network; R₁ – Thermal agent storage tank for heating or cooling; R₂ – Domestic hot water storage tank; VCV – Fan coils floor/ceiling unit; WWHP – Water-water heat pump; CWST - Cold Water Supply Tank, PV System – Photovoltaic Systems

2. Infrared thermography method of buildings. Principle, parameters and sources of error

Infrared (IR) thermal imaging cameras produce images of thermal patterns and are calibrated to measure the emissivity of surfaces in an area, at different temperature ranges [13].

The focusing of the radiation is achieved using a lens. The camera sensor detects the infrared radiation and converts it into electrical response signals that are digitally converted into colored pixels (images whose colors correspond to the temperature levels of the surface). The colors are established by mapping the intensity of the infrared radiation (temperature) onto a color palette (false color), established as follows: warm colors (white/yellow/red) allocated to high temperatures, and cool colors (blue/violet) for low temperatures. This conversion transforms the invisible radiation into visible images on the thermal imaging camera screen. With the help of

the camera software, the thermographic images are analyzed and these differences are quantified. This technology makes it possible to visualize the surface temperature of objects, that is to say the effect of heat transfer by conduction from the interior to the surface, which makes it possible to evaluate the amount of radiated heat, which is associated with the estimation of the body's surface temperature.

An important parameter of thermal imaging cameras is the measurement accuracy which is dependent on: emissivity, ambient temperature, wind speed and distance from the target. Another advantage of this method is that measurements can be made at a distance from the object, although atmospheric conditions can affect the amount of energy detected as a result of absorption. Emissivity depends greatly on the material of the thermographed surface or their coating materials. In practice, reading is influenced by emissivity less than or equal to 0.5. Therefore, emissivity can introduce measurement errors if not corrected.

Another possible source of error is the loss of energy in the transmission of radiation from the object being measured to the detector. Particles that may be present in the atmosphere (water vapor, carbon dioxide molecules and large size ozone) will attenuate the radiation, as well as the scattering effects of dust particles and water droplets. This attenuation produces two main transmission bands, approximately 3-5 μm and 8-12 μm . Thermal imaging cameras are designed to respond to one or the other of the bands, thus being insensitive to absorption effects. For high-performance cameras, the 8-13 μm band is generally preferred due to its greater sensitivity to objects at ambient temperature and good transmission through smoke. Cameras that transmit in the 3-5 μm band are more suitable for hotter objects or if sensitivity is less important than contrast.

Air temperature influences the temperature of the thermal imaging camera, which can lead to erroneous measurements. For this reason, thermal imaging cameras have an internal compensation system that corrects this variation. At very high or very low temperatures, there is a risk that these equipment will lose their stability, and at high temperatures the thermal information may be transmitted erroneously, especially when working with reflective surfaces.

Measurements obtained by thermography can be influenced by wind. Thus, winds with a speed exceeding 5 m/s will increase heat transfer from the surface, and higher heat losses by convection can reduce the surface temperature. Therefore, outdoor inspections in windy conditions (above 5 m/s) should be avoided during measurements. Also, when identifying air leaks around openings, strong winds will make them easier to detect during the inspection of interior windows and doors.

Another factor that can disrupt the thermal imaging measurement process is the distance and the angle of visibility, factors that play an important role in the interpretation of the results. It is obvious that the resolution decreases with increasing distance between the object and the thermal imaging camera (each point on the thermographic image corresponds to a specific area of the surface of the thermographed object, so as the distance increases, each point on the image will have to represent a larger surface area of the object). Therefore, this is the explanation for the fact that some details are lost. On the other hand, orienting the camera at angles

smaller than 90 degrees will obtain less information, but even for this type of orientation the images can still be distorted, depending on the surface material and its ability to radiate in different directions.

In conclusion, the images obtained are digital (visual) images that show that the hotter the object, the brighter it appears on the screen of the thermal imaging camera. In raw infrared radiation, a white color represents a hot area, while a dark color represents a cooler area. Thus, irregular thermographic patterns, called “thermal anomalies” (increases or decreases in surface temperature or retained residual heat) that indicate specific problems, can be easily identified. Therefore, the thermography method can be used either for building audits in order to establish renovation solutions or to assess the functional/defective state of equipment or installation systems. Compared to other types of methods, IR thermography is fast and accurate.

3. The role of thermography in the energy assessment of buildings

In the process of energy assessment of buildings, the thermography method is used to visualize and quantify temperature variations on the surfaces of building elements or services systems. The process is based on the detection of infrared radiation emitted by building elements (envelope and installation systems), which varies depending on temperature.

The use of the thermography method in the energy assessment of the building is a valuable tool for inspecting and performing inspections, considered very useful primarily because it is a non-destructive method. This method allows the detection of zones and mode where is transferred through the building envelope. The data collected allows to clarify the operating conditions of the installation systems (heating, ventilation, air conditioning, cold and hot water supply, electrical), service systems that are difficult to access being buried (in walls, screed, ceilings, etc.) or apparently being masked by various elements (plasterboard cladding, false ceilings, etc.). The information collected is used to identify and locate potential problems, quantify potential energy savings, schedule interventions and establish priorities for preventive and predictive maintenance or the need for immediate service to minimize the risk of failure.

4. Thermography of areas identified with suspected energy losses

4.1. Laboratory building description

The laboratory building, which is located in Timisoara, Romania, is constructed of Porotherm hollow brick with dimensions of 250 x 300 x 238 mm, and the interior cladding is made of 12.5 mm thick gypsum boards. The building is insulated on the outside with 5 cm polystyrene and is naturally ventilated. The roof of the building is a non-circulatory terrace with a slope of 3 degrees and is made of prefabricated sandwich panel sheets and polyurethane foam. An image of the building is shown in Figure 3.



Fig. 3. Laboratory building - Image

4.2. Potential energy loss areas

From the point of view of the envelope elements, the areas generating considerable losses are specified in Figure 4. Practically, the main areas with major energy losses (marked in red in the figure), which were investigated, refer to:

- the water tank from which the circulation pump for free cooling is powered and respectively the water-to-water heat pump that provides energy for heating and cooling the building as well as for hot water consumption;
- thermal bridges in the foundation area at the entry points of the power cables, but also in the roof and window areas;
- thermal energy losses through other entry gaps of various power cables or pipes for water supply.

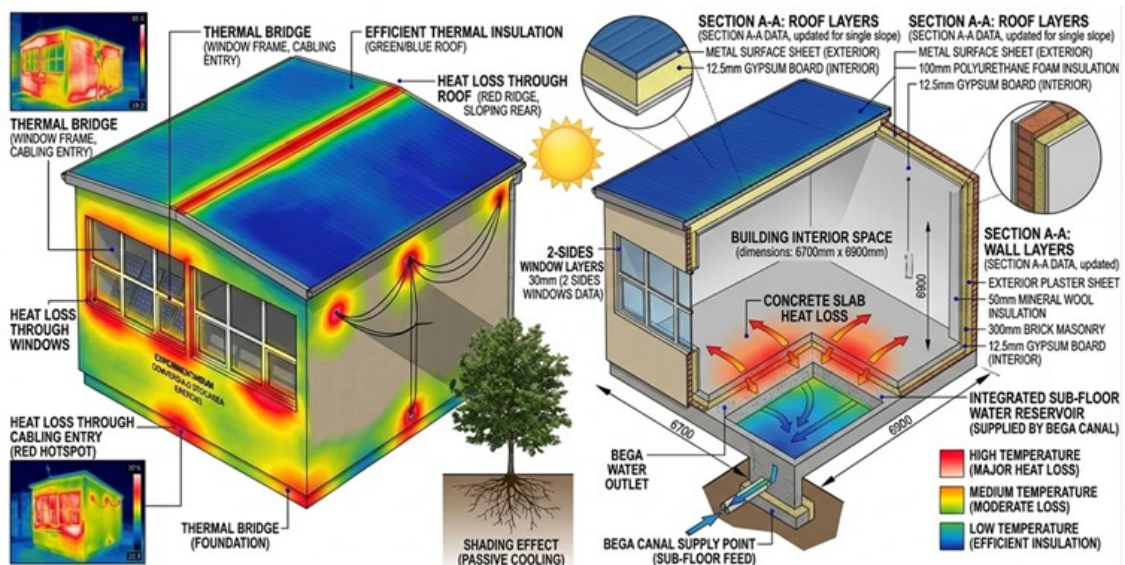


Fig. 4. Integrated thermographic analysis: Model

5. Results and Discussion

The results of thermography of areas with potential energy leaks are presented in Fig. 5.

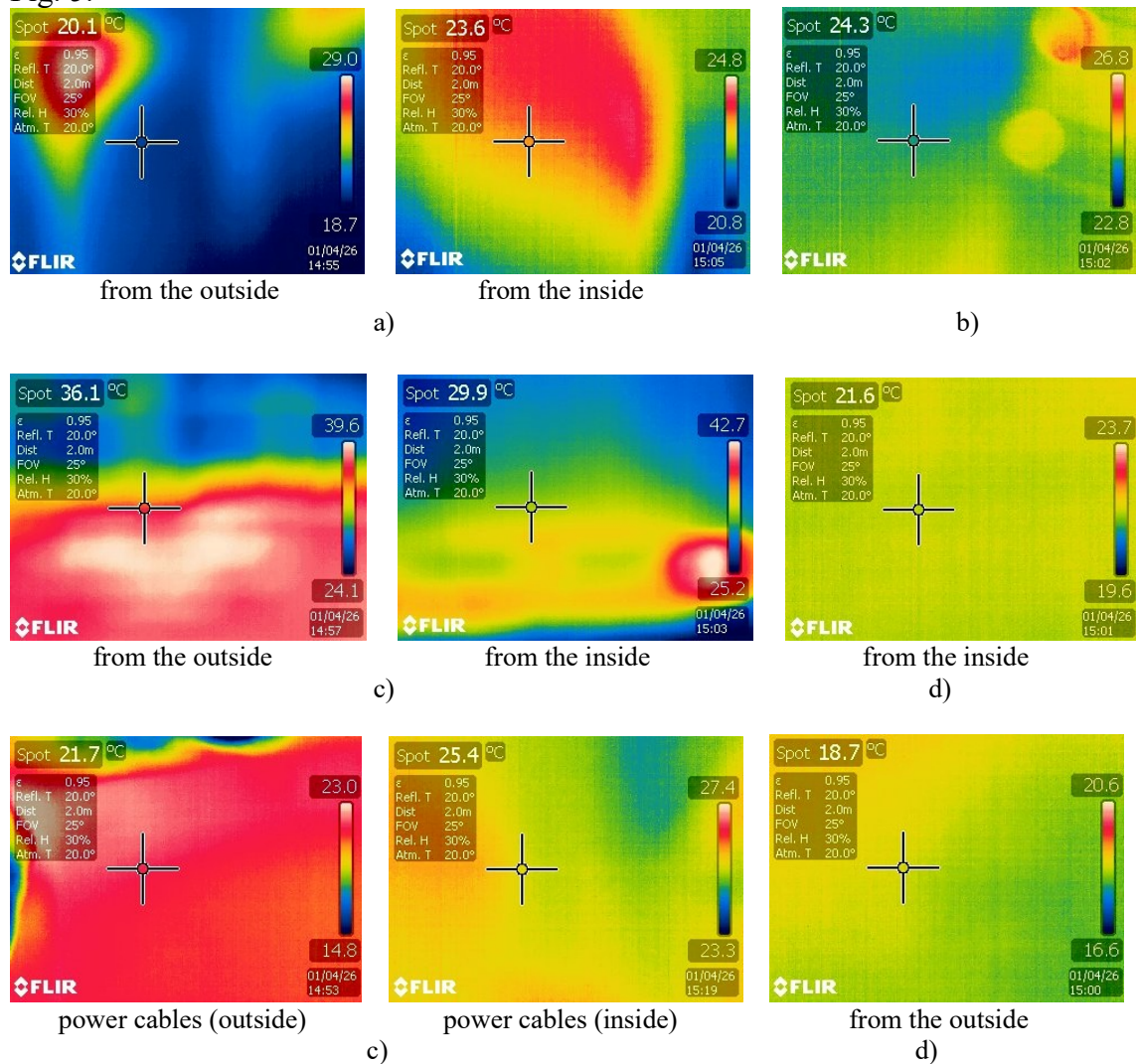


Fig. 5. Energy leaks - thermography of the laboratory building

- a) Heat leaks around door to the outside, b) Poor ceiling insulation, c) Heat leaks around windows, d) Heat leaks around cold water supply tank (CWST), e) Heat leaks around cable and pipe penetrations zones through walls f) Poor floor insulation

Thermal images were taken of the windows, door, ceiling, floor, the water tank and areas where cables and pipes pass through the walls in order to check for heat leaks, infiltrations and thermal bridges that cannot be seen with the naked eye. Analyzing the thermographic images, significant temperature differences (between inside and outside) are found in the analyzed areas.

To obtain the results, both exterior and interior thermography were performed because this combination offers complementary perspectives. Interior thermography was used to precisely identify air leaks and thermal bridges, while exterior thermography was used to verify the overall picture of potential energy losses (shown in Figure 4). It can be seen that results with greater accuracy and more detail are obtained with interior thermography.

For this reason, the following measures are proposed:

- insulating the floor or at least of the cold water supply tank (CWST) - on the contour;
- insulating the gaps for cable/pipe penetration through the envelope elements;
- restoring the door insulation in areas where it has heat leaks;
- solving thermal bridges around the windows - areas with the greatest losses.

4. Conclusions

The use of the thermography method of building elements is a valuable tool for inspecting and evaluating buildings, being useful primarily because it is a non-destructive method. For the "Energy Conversion and Storage" laboratory building, possible measures that can be taken to bring the building into a class higher than energy class C in which the building was evaluated after optimizing the installation systems that serve it were identified. Basically, passive measures were evaluated through which interventions that can be made to the building (walls, ceiling, floor, door, windows, water tank located under the foundation of the building - CWST) can contribute to reducing energy requirements. Thus, all these areas identified as having potential for energy transfer to the outside were thermographed. Following the evaluation of the thermographic images, insulation measures and, respectively, replacement of some elements were proposed, measures that the authors will address in future studies. The study conducted by the authors contributes to the identification of energy losses, to the establishment of opportunities for improving energy practices and to the implementation of all proposed measures that will contribute to the reduction of carbon emissions and can bring progress in cost-benefit applications for Politehnica University Timisoara. Therefore, awareness of the use of scientific tools for the study and analysis of energy performance is a current need for all types of energy users with applicability in all life stages of buildings.

References

- [1] M. Prundea, "How will electricity consumption and production evolve in Romania in the coming years? ANRE's official estimates", Available at: <https://www.mediafax.ro/economic>, accessed: 03 April 2026.
- [2] UN Environment Programme, "The Global Alliance for Buildings and Construction (GlobalABC)", Available at: <https://www.unep.org/topics/cities/buildings-and-construction/global-alliance-buildings-and-construction-globalabc>, accessed: 03 April 2026.

- [3] Isover Saint - Gobain, "Consumul de energie într-o clădire", Available at: <https://www.isover.ro/consumul-de-energie-intr-o-cladire>, accessed: 04 April 2026.
- [4] Nearly-zero energy and zero-emission buildings. Available online: https://energy.ec.europa.eu/topics/energy-efficiency/energy-performance-buildings/nearly-zero-energy-and-zero-emission-buildings_en#:~:text=European%20Union,%202025-,Nearly-zero%20energy%20buildings,the%20energy%20efficiency%20first%20principle. (accessed on 24 February 2026).
- [5] Ministry of Regional Development and Public Administration. Methodology for calculating the energy performance of buildings, Indicative Mc 001-2022; Publisher: Official Gazette of Romania, Part I, No. 46 bis/17.I.2023, Bucharest, Romania, 2023; pp. 69–77.
- [6] A. M. Omer, „Energy, environment and sustainable development in Renewable and Sustainable Energy Reviews”, vol. 12, no. 9, December 2008, pp. 2265-2300.
- [7] European Parliament and Council of the European Union. Directive (EU) 2024/1275 on the energy performance of buildings (recast). Official Journal of the European Union 2024, Series L, pp. 2-14.
- [8] Al-Obaidi, K.M.; Omrany, H. Carbon Technologies and Decarbonisation Strategies in Buildings: A Scoping Review and Conceptual Framework. *Human Settlements and Sustainability* **2025**. <https://doi.org/10.1016/j.hssust.2025.12.001>.
- [9] Balaras, C. A.; Gaglia, A. G.; Georgopoulou, E.; Mirasgedis, S.; Sarafidis, Y.; Lalas, D. P. European residential buildings and empirical assessment of the Hellenic building stock, energy consumption, emissions and potential energy savings. *Building and Environment* **2007**, *42*(3), 1298-1314. <https://doi.org/10.1016/j.buildenv.2005.11.001>.
- [10] L. Lariosa, E. A Carcasona, „The role of thermography in the energy assessment of buildings”, in Conference: International Conference on Technological and Social Innovations, Cebu City, Philippines, 2018.
- [11] Tokar, A.; Muntean, D.; Tokar, D.; Bisorca, D. Decarbonization of Heating and Cooling Systems of Buildings Located Nearby Surface Water Sources: Case Study. *Energies* **2024**, *17*(15), 3673. DOI: 10.3390/en17153673.
- [12] Tokar, A.; Muntean, D.; Tokar, D.; Bisorca, D. Experimental Study on the Sustainability of Harnessing the Thermal Potential of Surface Waters for Building Decarbonization. *Buildings* **2026**, *16*, 445. DOI: 10.3390/buildings16020445.
- [13] C.A. Balaras, A.A. Argiriou, „Infrared thermography for building diagnostics”, *Energy and Buildings*, vol. 34, Issue 2, 2002, pp. 171-183.

The correlation between biophilic strategies and the energy performance of buildings

Corelația dintre strategiile biofilice și performanța energetică a clădirilor

Alexandra Rusen

RU-LU WORK EXPRES WEST SRL

9 May Street, No. 41, Moldova Noua, Caras Severin, Romania

E-mail: rusenalexandra97@gmail.com

DOI: 10.37789/rjce.2026.17.3.15

Abstract: *This article analyzes the relationship between the integration of biophilic design principles in architecture and the energy performance of buildings. Strategies such as natural lighting, natural ventilation, and the integration of vegetation are evaluated, highlighting their impact on energy consumption and indoor comfort. The study demonstrates that biophilic design is not only an aesthetic approach, but also an effective tool for optimizing the energy performance of the built environment.*

Key words: *biophilic design, natural ventilation, materiality, vegetation, stack effect (natural draft), skylight, orientation.*

1. Introduction

The concept of biophilia was introduced and developed by Edward O. Wilson, who defined it as “the innate tendency of humans to seek connections with nature and other forms of life.”

This idea is based on the fact that, from an evolutionary perspective, humans developed in direct contact with the natural environment, and this relationship has remained deeply rooted in human psychology and physiology. This predisposition has evolutionary origins and significantly influences mental state, health, and human behavior. In the context of the built environment, biophilia forms the theoretical foundation of biophilic design, which aims to integrate natural elements into architecture in order to improve quality of life and spatial performance.

In the current context of climate change and the increasing energy consumption in the construction sector—accounting for approximately 40% of total global energy use—there is a growing interest in sustainable design strategies. Within this framework, the concept of biophilia, introduced by Edward O. Wilson, has become an important theoretical reference, defining the innate human tendency to seek connections with nature.

Recent research highlights that the integration of biophilic principles in architecture not only benefits users' health and well-being, but also has a significant impact on the energy performance of buildings. Studies conducted by Stephen R. Kellert emphasize the role of biophilic design in creating sustainable built environments, while reports published by the World Green Building Council underline the connection between passive strategies (such as natural lighting and natural ventilation) and reduced energy consumption.

Furthermore, specialized literature indicates that the use of natural elements—such as integrated vegetation, natural materials, and the optimization of the indoor–outdoor relationship—contributes to improving the indoor microclimate and reducing the energy demand for heating, cooling, and artificial lighting. However, there is still a lack of studies that directly quantify the correlation between biophilic strategies and energy performance, particularly in the context of single-family housing in Eastern Europe.

2. Strategies applicable in architecture

This study aims to investigate the correlation between biophilic strategies and the energy performance of buildings by addressing the following main research directions: the identification and systematization of the conceptual framework and the main biophilic strategies applicable in architecture; the evaluation of the impact of these strategies on building energy consumption; the analysis of the relationship between indoor comfort parameters and the energy efficiency of built spaces; the development of a case study on semi-detached house dwelling in order to highlight the practical applicability of biophilic principles; and the formulation of well-founded recommendations for integrating biophilic strategies into the architectural design process.

• Identification and Systematization of the Conceptual Framework and Main Biophilic Strategies Applicable in Architecture

The identification and systematization of the conceptual framework of biophilia, as well as of the main biophilic strategies applicable in architecture, represent an essential step in establishing the theoretical foundation of this research. The concept of biophilia, introduced by Edward O. Wilson, describes the innate human predisposition to develop a connection with nature, with significant implications for human health and behavior [1].

In the field of architecture, this concept was further developed and operationalized by Stephen R. Kellert, who defines biophilic design as an approach aimed at integrating nature into the built environment, contributing to the creation of healthy and sustainable spaces [2]. Subsequently, research has been expanded through a clearer structuring of biophilic strategies, particularly in the work of Browning et al., which proposes a model based on three main categories: nature in the space, natural analogues, and nature of the space [3].

According to these studies, the direct integration of nature (nature in the space) includes elements such as vegetation, natural light, water, and natural ventilation, being associated with improved environmental comfort and reduced energy consumption through passive strategies [3]. Indirect integration (natural analogues) involves the use of natural materials, forms, and textures inspired by nature, contributing to the creation of a psychologically supportive indoor environment [2].

The third category, nature of the space, refers to spatial configurations inspired by the natural environment, including features such as open perspectives, gradual transitions between interior and exterior, and variations in light and volume. These characteristics enhance user experience and contribute to the creation of a built environment adapted to fundamental human needs [3].

Furthermore, reports published by the World Green Building Council highlight that biophilic strategies can have a significant impact on building performance, particularly by reducing energy consumption and improving indoor environmental quality [4].

Therefore, the systematization of these strategies provides a coherent framework for analyzing the relationship between biophilic design and energy performance, demonstrating that biophilia is not only a theoretical concept but also a practical tool for optimizing building performance.

• *Evaluation of the impact of these strategies on building energy consumption*

The analysis of the energy impact of biophilic strategies highlights that they are not merely aesthetic or psychological interventions, but effective mechanisms for optimizing building energy consumption. The specialized literature indicates a direct correlation between the integration of natural elements and the reduction of energy demand for lighting, heating, and cooling.

The optimized use of natural light represents one of the most effective biophilic strategies with a direct energy impact. Studies show that the integration of daylighting can reduce energy consumption for artificial lighting by approximately 20% to 60%, depending on building typology and the adopted design solutions [5].

Moreover, solar gains contribute to the passive heating of spaces during the cold season, reducing the energy demand for heating. However, the lack of solar control measures may lead to overheating during the warm season, highlighting the need for complementary solutions such as shading devices or high-performance glazing [6].

Natural ventilation significantly contributes to reducing the energy consumption associated with mechanical cooling systems. Its use can decrease cooling energy demand by up to 30% under certain climatic conditions [7].

At the same time, natural ventilation improves indoor air quality and helps maintain adequate thermal comfort, reducing dependence on HVAC systems [8].

The integration of vegetation into architecture has a direct impact on the microclimate and on building energy performance. Vegetation contributes to lowering

outdoor temperatures through shading and evapotranspiration processes, thereby reducing cooling demand [9].

Green roofs can reduce heat flux through the building envelope and may lower indoor temperatures by approximately 1–3°C during summer periods [10].

The use of natural materials contributes to regulating indoor comfort conditions through their hygrothermal properties. Materials with high thermal mass can reduce temperature fluctuations and the energy demand for heating and cooling [6].

The energy impact of biophilic strategies is maximized when they are integrated within a holistic approach. The combination of daylighting, natural ventilation, and integrated vegetation can lead to a significant reduction in the overall energy consumption of buildings [3].

- ***Analysis of the relationship between indoor comfort parameters and the energy efficiency of built spaces***

The analysis of the relationship between indoor comfort parameters and the energy efficiency of built spaces highlights the interdependence between the environmental conditions perceived by users and the energy consumption required to maintain these conditions within optimal limits. Indoor comfort parameters—such as air temperature, relative humidity, air quality, and daylight levels—directly influence the energy performance of buildings, as their regulation involves the use of heating, cooling, ventilation, and artificial lighting systems [6].

The specialized literature emphasizes that optimizing these parameters through passive strategies, characteristics of biophilic design, can lead to a significant reduction in energy consumption without compromising user comfort. For instance, the use of natural lighting and natural ventilation reduces dependence on mechanical systems [5], [7], while the integration of materials with high thermal mass contributes to stabilizing indoor conditions and reducing temperature fluctuations [6].

At the same time, studies on passive climate control highlight that maintaining thermal comfort can be achieved by harnessing natural resources such as solar radiation, air movement, and the thermal mass of materials, thereby reducing the demand for conventional energy [8]. In this context, biophilic strategies—such as the integration of vegetation and the optimization of the indoor–outdoor relationship—contribute to improving the indoor microclimate and increasing the energy efficiency of buildings [9], [10].

Thus, a direct relationship can be observed between the enhancement of indoor environmental quality and energy efficiency, provided that design solutions are coherently integrated from the conceptual stage. In this regard, biophilic design can be considered an integrated approach that not only improves indoor comfort but also optimizes the energy performance of built spaces by leveraging natural resources and reducing dependence on active systems [3].

3. Case study: application of biophilic principles in a single-family dwelling

The development of a case study on a semi-detached house dwelling aims to highlight the practical applicability of biophilic principles and to analyze their impact on energy performance and indoor comfort. The case study represents a commonly used method in architectural research, allowing the correlation of the theoretical framework with concrete design solutions [2].

The analyzed dwelling is configured in accordance with biophilic design principles, through the integration of strategies such as optimal orientation relative to cardinal directions, maximization of natural lighting, implementation of natural ventilation by positioning openings on opposite facades, and the use of natural materials. These interventions contribute to reducing energy consumption and improving indoor environmental quality, being consistent with passive design strategies described in the specialized literature [6], [7].

At the same time, the natural variation of light within the interior space supports the principles of biophilic design by reproducing natural rhythms and enhancing the visual and psychological comfort of users [3]. Thus, the integration of daylight becomes not only a functional element but also an essential component in shaping a qualitative and sustainable spatial experience.

The analyzed case study focuses on a duplex residential building (semi-detached house) with a height regime of ground floor + one upper floor (P+1), characterized by a simple, compact volumetry and an architectural expression based on the use of natural materials and a direct relationship with the outdoor environment.



Fig. 1. Architectural rendering of the duplex as a case study

The overall configuration of the building highlights a contemporary approach in which biophilic principles are integrated both at a functional and at a compositional level.

The analyzed floor plans highlight a coherent functional organization, in which spaces are configured in an efficient, compact, and ergonomic manner, adapted to users' needs and aligned with the principles of biophilic design. Their dimensions are established in such a way as to avoid unnecessary surfaces, optimizing circulation flows and the use of interior space.

The daytime area, located on the ground floor, is conceived as an open-plan space integrating living, dining, and kitchen functions, promoting both visual and functional continuity. This configuration allows for a direct relationship with the exterior through large openings towards green spaces, facilitating the penetration of natural light and creating a constant connection with the natural environment.

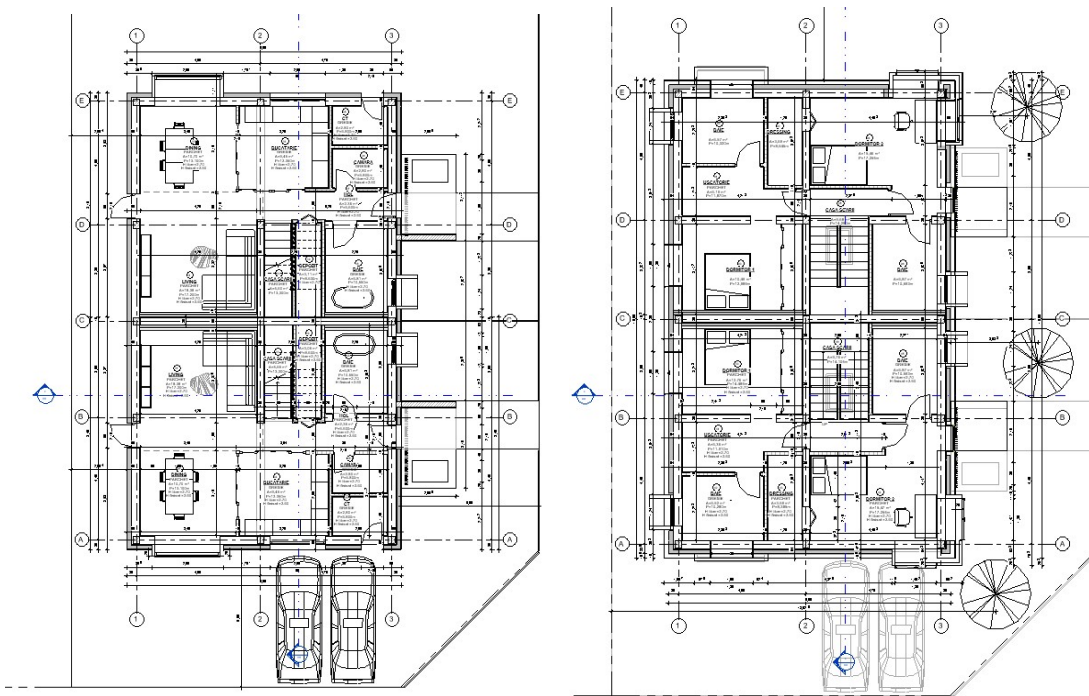


Fig. 2. Ground floor plan and first floor plan of the duplex

On the upper floor, the night-time spaces are organized to ensure privacy while maintaining a direct relationship with the exterior, through the orientation of rooms towards the green areas of the site. Each room is ergonomically dimensioned, ensuring a balance between functionality and comfort without overcrowding the space.

A central element of the spatial organization is the staircase, which functions not only as a vertical circulation element but also as a biophilic and climatic core of the dwelling. It facilitates natural ventilation and the integration of vegetation, contributing to the creation of a favorable indoor microclimate.

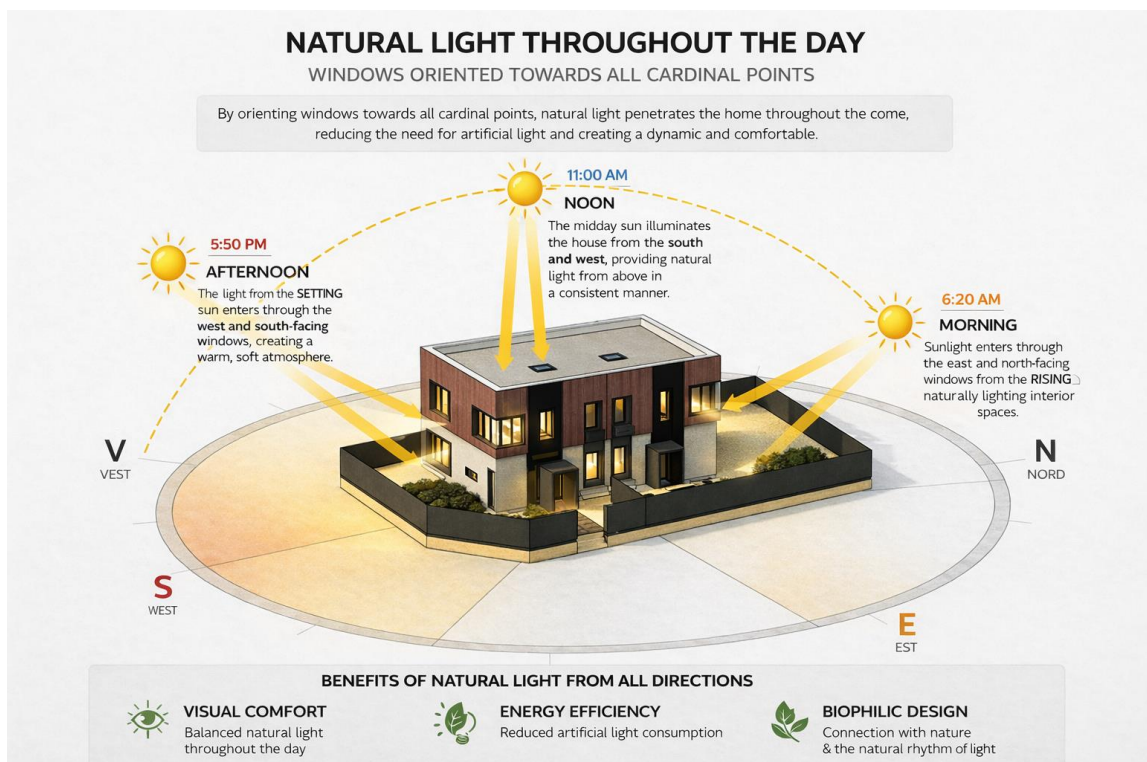
The interconnection of spaces is achieved in a fluid manner, without major discontinuities, allowing for a unified perception of the dwelling and a continuous relationship with nature. The placement of the building within a natural setting is enhanced through the orientation of openings towards the exterior, providing visual connections to vegetation and ensuring direct exposure to the natural environment. The space is not merely inhabited, but experienced in direct relation to nature.

Thus, the planimetric organization reflects a contemporary approach in which spatial efficiency, ergonomics, and the integration of nature are correlated, generating a balanced, sustainable living environment adapted to current needs [3].

The distribution and sizing of façade openings have been designed to ensure a constant supply of natural light throughout the day, by orienting windows towards all cardinal directions. As a result, natural light gradually penetrates interior spaces depending on the position of the sun, contributing to the creation of a dynamic and visually balanced environment.

The southeast and southwest orientations favor solar gains during morning and afternoon periods, while openings towards other directions complement daylighting throughout the entire day. This strategy reduces dependence on artificial lighting and contributes to optimizing the building's energy consumption [5].

An essential element of the case study is the relationship between the interior space and the external environment, achieved through large glazed surfaces, terraces, and the integration of vegetation in the immediate proximity of the building. These solutions facilitate natural lighting, support natural ventilation, and generate a favorable microclimate, with a positive impact on energy consumption [3], [9].



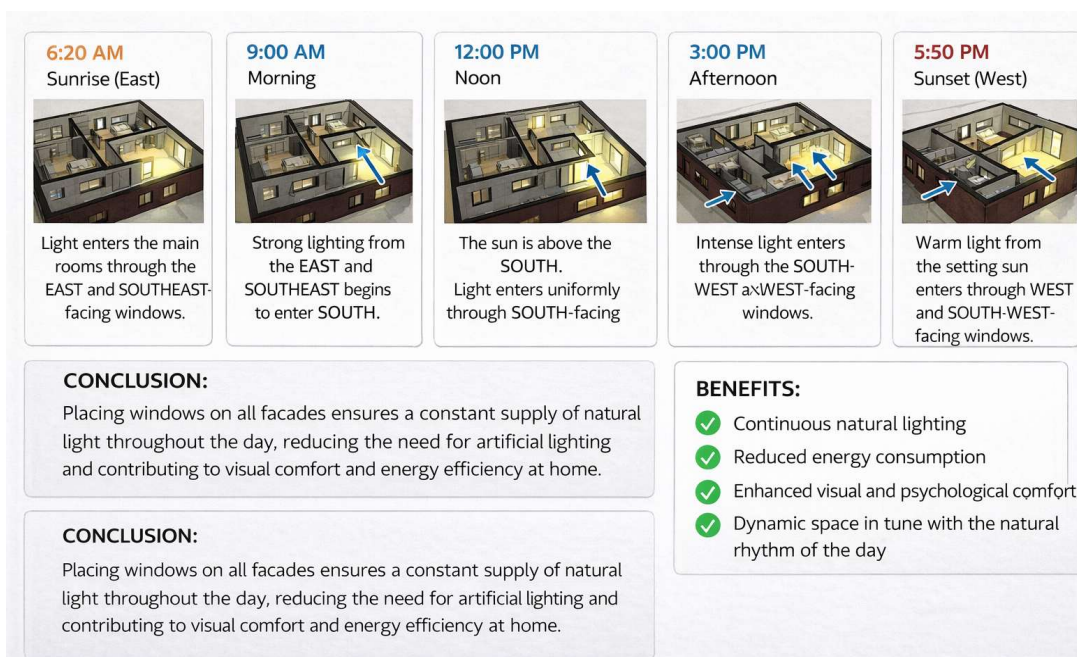


Fig. 3. Sunlight study – highlighting the contribution of natural light throughout the day

Furthermore, the integration of vegetation and materials with hygrothermal properties contributes to stabilizing indoor conditions and reducing temperature fluctuations, thereby decreasing the energy demand for heating and cooling [6], [10]. Thus, the analyzed dwelling demonstrates how biophilic strategies can be coherently implemented, generating benefits both in terms of energy performance and user comfort.

An essential aspect of optimizing natural ventilation in the analyzed dwelling is the use of the stack effect, generated by temperature and pressure differences between the lower and upper areas of the building. A hybrid ventilation system is therefore proposed, combining natural ventilation during the warm season with mechanical ventilation with heat recovery during the cold season. Fresh air enters through windows located on the southern façade, is drawn through the interior spaces, and is subsequently exhausted through a roof window (Velux type) positioned above the staircase, in the northern area. This configuration promotes the creation of an upward airflow, driven by the natural tendency of warm air to rise, achieving efficient natural ventilation without additional energy consumption [7].

Through this mechanism, continuous renewal of indoor air is ensured, contributing to maintaining air quality and reducing the need for mechanical ventilation. At the same time, this passive ventilation system facilitates the removal of overheated air during the warm season, playing an important role in the building's natural cooling strategy [8]. The integration of such a solution highlights a coherent application of biophilic and bioclimatic principles, by harnessing available natural resources and reducing dependence on active HVAC systems.

An innovative element proposed within the analyzed dwelling is the integration of a vertical greenery system located in the staircase, correlated with the natural ventilation mechanism based on the stack effect. In this area, a green wall composed of potted plants arranged on metal supports is proposed, characterized by a substantial vegetal volume that contributes to creating a favorable indoor microclimate. The system is complemented by a sprinkler assembly that sprays water onto the vegetation, facilitating evapotranspiration processes and the natural cooling of the air.

The fresh air introduced through the lower facades of the building passes through this vegetated zone, where it is partially cooled and humidified, and is subsequently exhausted through the upper roof window positioned above the staircase. Thus, the staircase functions as an active “ventilation chimney,” where the interaction between vegetation, water, and airflow contributes to improving indoor air quality and reducing air temperature, in accordance with the principles of passive evaporative cooling [8], [9].

The sprayed water is collected at the base of the green wall through a drainage grid and directed to an external reservoir, allowing its recirculation and reducing resource consumption. This integrated system highlights a sustainable approach in which biophilic elements are correlated with building services solutions, contributing both to energy efficiency and to the creation of a healthy and comfortable indoor environment [3].

The natural ventilation system based on the stack effect, integrated with the green wall and evaporative cooling elements, demonstrates high efficiency during the warm season, contributing to the reduction of overheating and the improvement of indoor thermal comfort.

Under high temperature conditions, warm air inside the dwelling accumulates in the upper part of the staircase and is evacuated through the roof window (Velux type). This process generates an intensified natural draft, which induces the intake of fresh outdoor air through openings located at the lower levels, particularly on the southern façade. Thus, a continuous airflow is created, contributing to the cooling of interior spaces without the use of mechanical air-conditioning systems [7].

During the cold season, natural ventilation through the stack effect is limited by keeping the roof window closed, in order to avoid heat losses. Under these conditions, the ventilation system is adapted through the integration of controlled solutions that maintain indoor air quality without compromising energy efficiency.

An effective solution consists in the use of a mechanical ventilation system with heat recovery (HRV – Heat Recovery Ventilation), integrated within the staircase area. The stale air extracted from the upper part of the dwelling passes through a heat exchanger, where it transfers thermal energy to the incoming fresh air from outside. In this way, indoor air renewal is ensured with minimal energy losses [6].

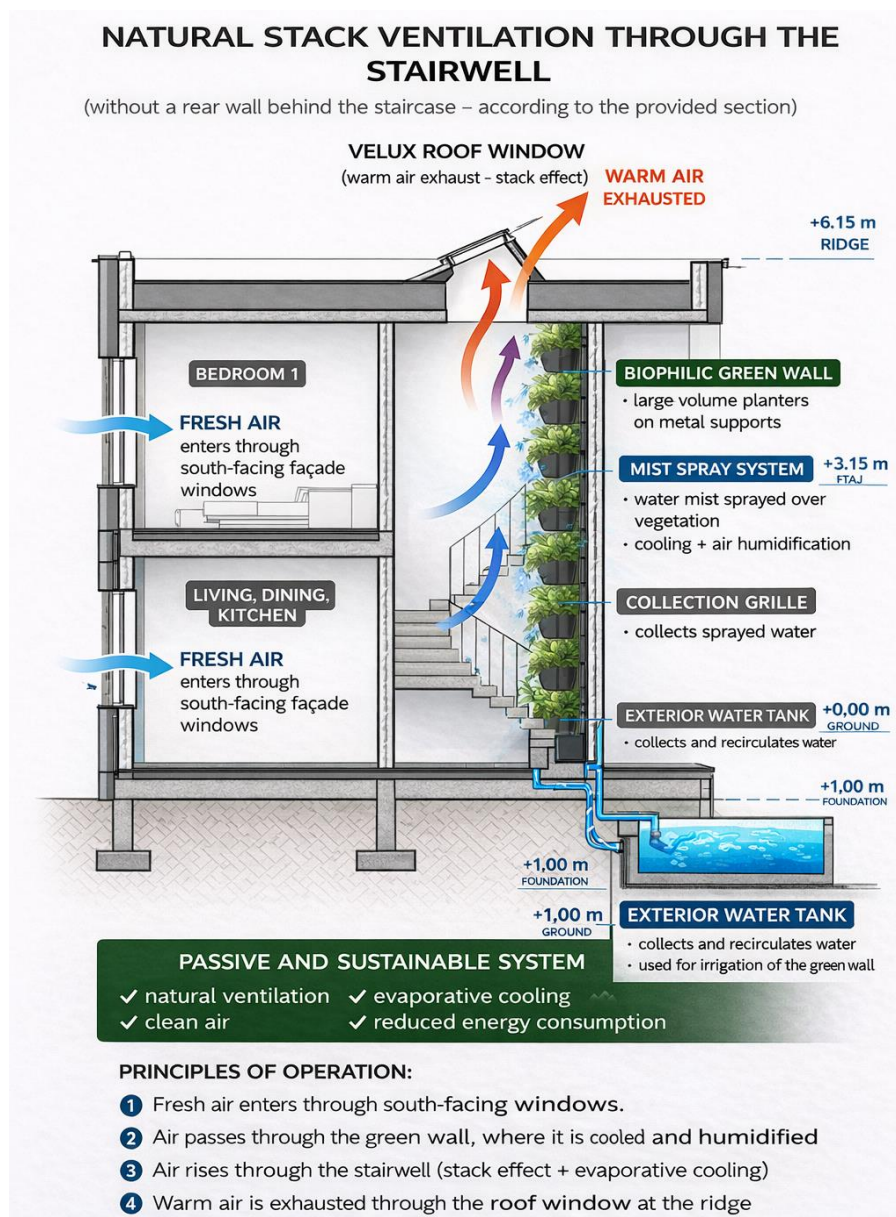


Fig. 4. Natural ventilation scheme based on the stack effect and integration of the biophilic green wall

Within the proposed system, the staircase functions as a warm air collection zone, without allowing direct exhaust to the exterior. The air is captured through extraction grilles and directed to the heat recovery unit, where thermal energy is reused. This solution maintains the principle of vertical air circulation, characteristic of biophilic design, but in a controlled and energy-efficient manner.

The green wall maintains its role during the cold season; however, the operation of the sprinkler system is reduced or adjusted to avoid excessive humidity. The vegetation continues to contribute to improving air quality and stabilizing the indoor microclimate.

Therefore, the proposed system operates differently depending on the season: in summer, natural ventilation through the stack effect ensures passive cooling of the building, while in winter, ventilation is controlled and based on heat recovery, reducing energy losses and maintaining indoor comfort [3], [6].

Consequently, the case study demonstrates that the application of biophilic principles in the design of single-family dwellings represents a viable solution for increasing energy efficiency and improving the quality of the built environment, confirming their relevance in contemporary architectural practice.

3. Conclusions

The conducted analysis highlights that the integration of biophilic principles into architectural design significantly contributes to improving both energy performance and indoor environmental quality. Through the use of passive strategies—such as natural ventilation, optimized daylighting, and the integration of vegetation—the dependence on mechanical systems is reduced, thereby lowering the overall energy consumption of the building.

The analyzed case study demonstrates the practical applicability of these principles in a contemporary single-family dwelling, in which spatial organization, orientation, and materiality are closely correlated with natural factors. The compact and ergonomic plan configuration enables efficient space utilization, while openings oriented towards all cardinal directions ensure a consistent supply of natural light throughout the day, contributing to visual comfort and reducing the need for artificial lighting.

A key element in the building's performance is the staircase, which becomes an active component of the natural ventilation system, functioning as a ventilation chimney based on the stack effect. The integration of the green wall, combined with a sprinkler system and water recirculation, enhances the efficiency of this mechanism through evaporative cooling processes and the improvement of indoor air quality.

Furthermore, the seasonal operation of the system—natural ventilation during the warm season and controlled ventilation with heat recovery during the cold season—highlights the adaptability and sustainability of the proposed solution. The integration of building services systems in correlation with biophilic strategies allows for the optimization of energy consumption without compromising user comfort.

The use of natural materials such as stone, wood, and fired ceramics contributes to the regulation of hygrothermal conditions and to the creation of a healthy indoor environment, while color schemes and the variation of natural light support a dynamic spatial experience aligned with natural rhythms.

In conclusion, the analyzed project demonstrates that biophilic design is not merely an aesthetic direction, but an integrated design strategy capable of addressing contemporary requirements related to energy efficiency, sustainability, and quality of living. The coherent implementation of these principles leads to the creation of balanced, efficient architectural spaces that are deeply connected to the natural environment.

References

- [1] E.O. Wilson, *Biophilia*, Harvard University Press, Cambridge, 1984.
- [2] S.R. Kellert, *Biophilic Design: The Theory, Science and Practice of Bringing Buildings to Life*, Wiley, New York, 2008.
- [3] W. Browning, C. Ryan, J. Clancy, *14 Patterns of Biophilic Design: Improving Health & Well-Being in the Built Environment*, Terrapin Bright Green, New York, 2014.
- [4] World Green Building Council, *Health, Wellbeing and Productivity in Offices*, World Green Building Council, London, 2014.
- [5] C.F. Reinhart, K. Voss, "Monitoring manual control of electric lighting and blinds", *Lighting Research & Technology*, nr. 3, 35, 2003, pp. 243–260.
- [6] N. Lechner, *Heating, Cooling, Lighting: Sustainable Design Methods for Architects*, Wiley, Hoboken, 2015.
- [7] F. Allard, *Natural Ventilation in Buildings: A Design Handbook*, James & James, London, 1998.
- [8] M. Santamouris, D. Asimakopoulos, *Passive Cooling of Buildings*, James & James, London, 1996.
- [9] E. Alexandri, P. Jones, "Temperature decreases in an urban canyon due to green walls and green roofs", *Building and Environment*, nr. 4, 43, 2008, pp. 480–493.
- [10] K.L. Getter, D.B. Rowe, "The role of extensive green roofs in sustainable development", *HortScience*, nr. 5, 41, 2006, pp. 1276–1285.

Perspectives and challenges of integrating high-entropy alloys into the HVAC industry through 3D printing

Perspective și provocări ale integrării aliajelor cu entropie ridicată în industria HVAC prin intermediul printării 3D

Gabriel-Victoria Mnerie^{1,2,3}, Evelin-Anda Laza¹, Emilia Dobrin²,
Lavinia-Ileana Sîrbu², Oleksii Gubenia⁴, Ninoslava Tihi⁵

¹ The National Institute of Research -Development for Machines and Installations Designed for Agriculture and Food Industry - INMA Bucharest
6, Ion Ionescu de la Brad Blv., Bucharest, Postal Code 013813, Romania
E-mail: gabriela.mnerie@yahoo.com, eleline_anda@yahoo.com

² National Research & Development Institute for Welding and Material Testing – ISIM Timisoara
30, Blv. Mihai Viteazu, Postal Code 300222, Timisoara, Romania
E-mail: gmnerie@isim.ro, lbuzatu@isim.ro, edobrin@isim.ro

³ Ioan Slavici University
144, Dr. Aurel Paunescu Podeanu street, 144, Timisoara, Postal Code 300587, Romania
E-mail: gabriela.mnerie@yahoo.com

⁴ National University of Food Technologies,
Volodymyrska street, 68, Kyiv, Postal code 01033, Ukraine
E-mail: gubena@meta.ua

⁵ The Higher Education Technical School of Professional Studies
2, Skolska, Novi Sad, Postal Code 013813, Serbia
E-mail: tihi@vtsns.edu.rs

DOI: 10.37789/rjce.2026.17.3.16

Abstract. *This study analyses the benefits of integrating high-entropy alloys (HEAs) into HVAC systems using 3D printing technologies. The results indicate high performance in corrosive environments and under thermal stress, optimizing critical components such as fans and heat exchangers. The paper introduces cost-effective repair methods and advocates for the standardization of additive manufacturing processes to maximize the impact of HEAs in high-performance industrial applications.*

Key words: 3D printing, High-Entropy Alloys, HVAC system, additive manufacturing

1. Introduction

Heating, ventilation, and air conditioning (HVAC) systems are integral to providing comfortable and healthy indoor environments across a diverse range of building types, from residential homes to large industrial complexes. Beyond maintaining optimal temperature and air quality, modern HVAC installations are expected to meet increasingly stringent standards for energy efficiency, environmental compliance, and long-term durability. As concerns about global energy consumption and climate change intensify, these systems have come under growing pressure to operate more sustainably and cost-effectively.

In parallel with these evolving requirements, the field of materials science has witnessed remarkable developments that directly impact HVAC performance. HEAs - compositions characterized by multiple principal elements in near-equimolar proportions - have emerged as a powerful alternative to conventional alloys. These novel alloys often exhibit superior mechanical, thermal, and chemical properties, including enhanced corrosion resistance and improved thermal stability [1, 2]. Such characteristics are particularly relevant for HVAC applications, where components must withstand corrosive environments, frequent thermal cycles, and mechanical wear over extended operating lifespans.

Compounding the appeal of HEAs is the rapid rise of additive manufacturing (AM), commonly known as 3D printing, as a cost-effective and material-efficient production technology. By building components layer-by-layer, AM processes facilitate complex geometrical designs, minimal material waste, and rapid prototyping. Consequently, 3D printing of HEAs represents a valuable avenue for addressing critical HVAC challenges: it enables the fabrication of intricate, custom-tailored parts with enhanced properties while simultaneously reducing maintenance costs and downtime through advanced repair methods. In particular, directed energy deposition (DED) has garnered attention as a means to efficiently restore worn or damaged HEA components, extending their useful life and curbing material wastage [3].

2. Background on HEAs

HEAs represent a novel class of materials in which multiple principal metallic elements, typically with atomic fractions ranging from 5% to 35%, coexist in near-equiatomic proportions. By comparison, conventional alloys are usually based on one primary element which dictates the bulk of the alloy's properties. The distributive nature of elemental constituents in HEAs leads to unconventional microstructures and confers multiple structural advantages, such as enhanced mechanical robustness and excellent thermal stability. This chapter provides an overview of the composition and microstructural characteristics of HEAs, referencing seminal studies that have shaped current understanding and applications of these innovative materials.

Fig.1 provides a visual overview of the concept of high-entropy alloys (HEAs), highlighting the balanced distribution of elements, the differences compared to conventional alloys, and the superior structural properties that make them suitable for advanced applications.

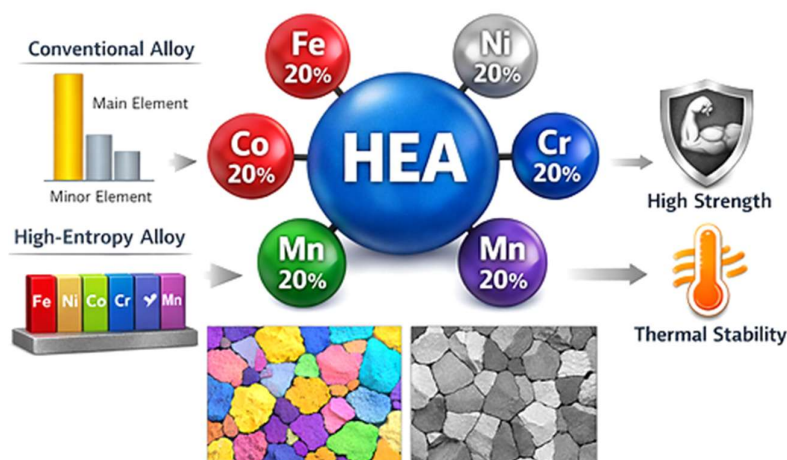


Fig. 1. Overview of the composition and microstructure of high-entropy alloys (HEAs)

2.1. Composition and microstructure

The key defining feature of HEAs is their high configurational entropy, derived from the presence of several principal elements in near-equiatomic ratios. This elevated entropy can stabilize simple solid-solution phases (i.e., face-centred cubic (FCC), body-centred cubic (BCC), or mixed phases) rather than complex intermetallic structures, thus contributing to outstanding strength, ductility, and thermal stability [4, 5]. For instance, Miracle and Senkov [4] underscore that the absence of dominant single-element phases in HEAs promotes equilibrium structures that are notably resistant to phase transformations. Such stability is especially critical for applications requiring extended service life at elevated temperatures or in highly corrosive environments.

Moreover, the characteristic multi-principal-element composition introduces several phenomena often referred to as the “core effects” of HEAs:

- High entropy effect: stabilizes simple solid-solution phases by increasing the overall entropy and lowering free energy;
- Sluggish diffusion effect: slows the rate of atomic diffusion, potentially improving creep resistance and dimensional stability;
- Severe lattice distortion: the presence of different atomic radii causes localized strain fields and can hinder dislocation movement, enhancing mechanical strength;
- Cocktail/ensemble effect: different elements can exert synergistic strengthening effects, collectively improving corrosion resistance, wear behavior, and other functional properties.

In practice, alloy design strategies for producing HEAs often rely on computational tools such as CALPHAD (CALculation of PHase Diagrams) to predict stable phases and optimize compositions prior to experimental validation. As a result, manufacturers can systematically explore countless multi-component systems to tailor specific properties (e.g., hardness, ductility, corrosion resistance) to meet application requirements in high-demand sectors.

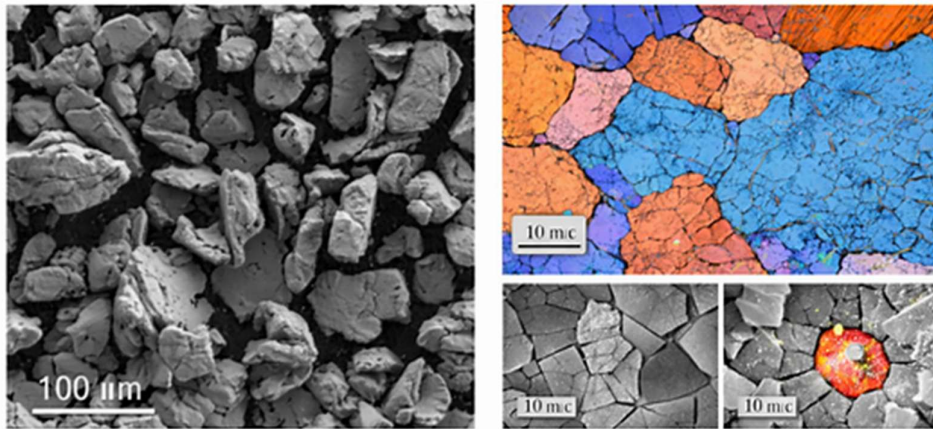


Fig. 2. Microstructure of CoCrFeMnNi HEA powder observed via scanning electron microscopy (SEM)

Representative examples of microstructural features

- FCC-dominant HEAs: commonly observed in systems such as CoCrFeMnNi (figure 2), the FCC structure lends excellent ductility and moderate strength. Zhu et al. [5] have demonstrated that tuning the relative ratios of elements can lead to substantial improvements in tensile strength without sacrificing elongation, making these alloys ideal for structural applications;
- BCC-dominant HEAs: BCC-based HEAs often exhibit higher strength than their FCC counterparts, though sometimes at the expense of ductility. Despite this trade-off, BCC structures can be favourable in applications where superior yield strength and hardness are prioritized (e.g., cutting tools or high-stress environments);
- Mixed FCC/BCC structures: some HEAs adopt dual-phase microstructures, combining the toughness of FCC phases with the high strength of BCC phases. This composite-like configuration can yield a unique balance of mechanical properties suitable for demanding environments, such as turbines and heat exchangers in energy systems.

The elevated configurational entropy derived from the balanced distribution of multiple elements explains why HEAs exhibit properties rarely found in traditional alloys. It is precisely this unique synergy - coupled with emerging manufacturing techniques like additive manufacturing - that positions HEAs as promising candidates for advanced structural and functional components in various industries, including the realms of heating, ventilation, and air conditioning (HVAC) discussed in subsequent chapters.

2.2. Properties relevant to HVAC applications

The unique composition and microstructure of high-entropy alloys provide a range of functional properties especially pertinent to the demanding conditions found in heating, ventilation, and air conditioning (HVAC) systems. By combining multiple principal elements with high configurational entropy, HEAs often outperform conventional alloys (e.g., aluminium, steel, copper) in areas critical to HVAC performance and longevity. This section details three key properties - corrosion resistance, thermal fatigue performance, and wear resistance - and highlights their relevance to HVAC applications.

Several material properties make HEAs attractive for HVAC applications:

2.2.1. Corrosion resistance

HVAC components frequently operate in environments where moisture, chemicals, or pollutants threaten the integrity of metallic parts (e.g., heat exchangers, piping, and condensing units). Many HEAs exhibit superior corrosion resistance due to their highly stable surface oxide layers and optimized chemical compositions. For instance, Shi et al. [6] point out that the multi-element nature of HEAs can promote uniform passivation, effectively slowing down corrosion-induced degradation. Additionally, the sluggish diffusion effect inherent in HEAs may further protect surfaces by limiting the transport of corrosive agents throughout the material.

In practical HVAC settings, improved corrosion resistance translates to:

- longer service life for components exposed to harsh conditions;
- reduced maintenance, as protective coatings or frequent replacements become less necessary;
- improved reliability, beneficial in large-scale installations (e.g., industrial cooling towers or district heating systems).

2.2.2. Thermal fatigue performance

Thermal fatigue arises when materials are subjected to regular heating and cooling cycles, causing repeated thermal expansion and contraction. Over time, these cycles can lead to crack initiation and propagation, reducing the component's service lifespan. HEAs, however, often exhibit excellent high-temperature strength and phase stability, making them well-suited to handle frequent temperature swings in HVAC equipment [7].

Schuh et al. [7] have shown that certain HEA compositions, especially FCC-dominated alloys, maintain their ductility and toughness at elevated temperatures. This characteristic is crucial in heat exchangers, compressors, and furnace systems, where components undergo cyclical thermal stresses. By incorporating thermally robust HEAs, HVAC systems can:

- minimize crack formation and fatigue-induced failures;
- operate more reliably for extended periods under fluctuating temperatures;
- reduce downtime associated with unplanned maintenance or part replacements.

2.2.3. Wear resistance

Moving components within HVAC systems - such as fan blades, valves, and pumps - are subject to frictional forces and mechanical wear, especially when handling dusty or corrosive airflows and water streams. The mechanical robustness of HEAs makes these alloys particularly advantageous for combating wear. Miao and Tsai [8] reported that the presence of multiple principal elements in HEAs induces a range of solid-solution or intermetallic phases, contributing to hardness, reduced friction, and lower wear rates.

From an industrial perspective, leveraging the wear resistance of HEAs in HVAC systems can:

- enhance operational efficiency by maintaining smoother surfaces;
- lower maintenance costs via elongated service intervals;
- improve overall system reliability, reducing the likelihood of critical failures in moving parts.

2.2.4. Comparison with conventional alloys

Although aluminium, steel, and copper have long been used in HVAC due to their availability, cost, and familiarity, HEAs offer a compelling alternative in environments where standard metals may rapidly corrode, fail under cyclic stress, or wear out prematurely. While some HEAs can be more expensive initially, their enhanced durability and improved operational efficiency have the potential to offset these costs over the long term. Moreover, the advent of additive manufacturing has made it more feasible to produce complex HEA geometries in a cost-effective and material-efficient manner, further bolstering their appeal for HVAC applications.

3. Additive manufacturing of HEAs

Additive manufacturing (AM), or 3D printing, has rapidly gained importance in the production of metallic components, offering the potential to reduce material waste, shorten lead times, and enable customized designs. In the context of high-entropy alloys (HEAs), AM methods amplify these benefits by providing precise control over microstructure, chemistry, and geometry - factors that can significantly impact an HEA's mechanical and thermal properties.

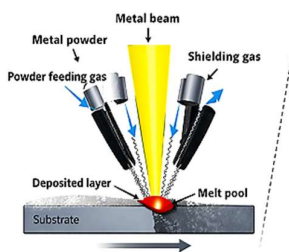
3.1. 3D printing techniques

The feasibility of 3D printing HEAs has been demonstrated using a range of powder-based and wire-based techniques, each with unique strengths and limitations regarding cost, build rate, part geometry, and mechanical properties [9, 10].

❖ Selective laser melting (SLM) (figure 2a):

- process overview: a laser selectively fuses regions of a powder bed in a layer-by-layer fashion;

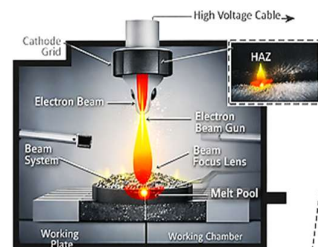
- advantages: high dimensional accuracy and surface finish; suitable for complex, intricate parts [10];
 - limitations: slower build rate than some deposition-based methods due to the layer-by-layer powder bed approach, and strict powder specifications to ensure part quality.
- ❖ Electron Beam Melting (EBM) (figure 2b):
- process overview: similar to SLM but employs an electron beam in a controlled vacuum environment;
 - advantages: faster build rates compared to SLM, lower residual stresses due to vacuum operation, and good consolidation for reactive materials (e.g., titanium alloys and certain HEA compositions) [11];
 - limitations: more expensive equipment, requirement for vacuum conditions, and potential challenges in controlling powder charging during the process.
- ❖ Laser Metal Deposition (LMD) (figure 2c):
- process overview: also known as Laser Cladding or Laser Direct Metal Deposition, this process delivers powder coaxially into a melt pool generated by a high-power laser scanning over a substrate [12];
 - advantages: suited for near-net-shape builds, gradient materials creation, or application of coatings. Often used in aerospace and energy industries for larger structural parts;
 - limitations: less precise than SLM for fine geometrical features, potentially leading to larger feature sizes and higher surface roughness.
- ❖ Directed Energy Deposition (DED) (figure 2d):
- process overview: a technique in which a heat source (laser beam, electron beam, or plasma arc) fuses material (either blown powder or fed wire) delivered through a nozzle mounted on a multi-axis system [9];
 - advantages: selective repair: DED can rebuild worn or damaged sections of a part, making it highly appealing for HVAC components requiring maintenance and retrofits; versatile: able to deposit material in any 3D path, enabling designs with internal channels or complex geometries; high deposition rates relative to powder-bed processes.
 - limitations: may yield coarser microstructures and require post-processing (e.g., machining, heat treatment) to achieve final desired tolerances and properties.



(a)



3D-Printed Cooling Manifold



(b)



3D-Printed Cooling Manifold

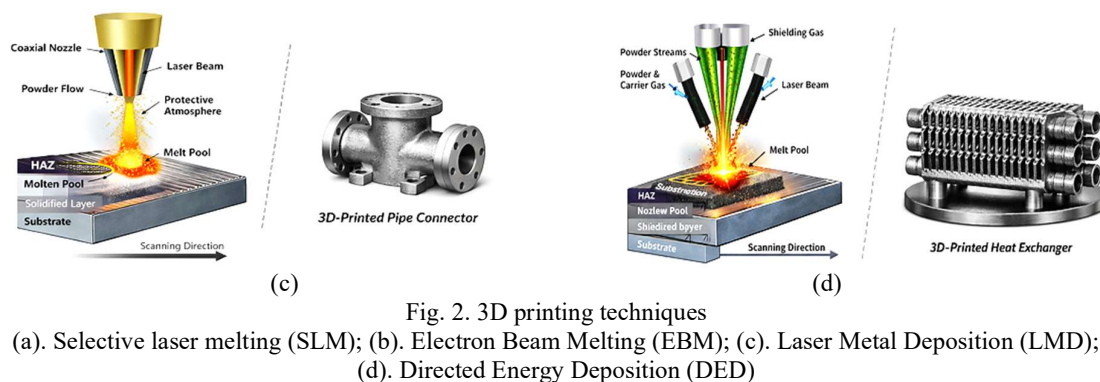


Fig. 2. 3D printing techniques

(a). Selective laser melting (SLM); (b). Electron Beam Melting (EBM); (c). Laser Metal Deposition (LMD); (d). Directed Energy Deposition (DED)

Among these techniques, Directed Energy Deposition has garnered particular interest for repair strategies in HVAC systems, due to its capability to pinpoint locations on worn or corroded components and rebuild them in situ. This localized approach minimizes material waste and reduces downtime, enabling a more cost-effective lifecycle for HEA-based HVAC parts [9].

Relevance to HVAC applications

HVAC systems often contain numerous custom metal parts (e.g., specialized fan blades, cones, ducts) that suffer from corrosion, thermal stress, or mechanical wear. In such scenarios:

- SLM or EBM may be beneficial for fabricating entirely new, complex HEA components, particularly where fitness-for-service depends on precise geometries or lightweight, lattice-like structures;
- DED or LMD become extremely valuable for on-site repairs or the remanufacture of critical sections, reducing the need to discard an entire part.

By selecting an appropriate AM method, engineers and technicians can tailor the build process to meet specific performance requirements - be it surface finish, dimensional accuracy, or throughput - while capitalizing on the robust material properties inherent in HEAs. In turn, such adaptability paves the way for longer service lives, enhanced efficiency, and lower maintenance costs in high-demand HVAC environments.

3.2. Advantages of 3D-printed HEAs

The process of additive manufacturing (AM), when applied to high-entropy alloys (HEAs), offers a host of benefits that extend well beyond those of conventional metal-forming methods. This is largely attributed to the synergy between the unique properties of HEAs - such as superior corrosion resistance, enhanced thermal fatigue strength, and robust wear behaviour - and the design freedoms enabled by AM. Figure 2 provides a conceptual illustration of the core advantages of 3D-printed HEAs for HVAC and other high-demand applications.

3.2.1. Geometrical complexity

One of the most significant benefits of additive manufacturing lies in its ability to produce complex geometries that are difficult - if not impossible - to achieve through traditional subtractive or casting-based processes. This is particularly valuable for HVAC systems, which may involve intricate heat exchanger designs, custom conduits, or optimized fan blade profiles.

- improved heat transfer: complex internal channels or cellular/lattice structures can be designed to increase surface area and optimize fluid flow, thereby improving thermal efficiency;
- design freedom for consolidation: AM enables part consolidation, reducing the total number of components and simplifying assembly [13].

Case example:

Using 3D-printed HEA heat exchangers featuring internal coolant channels optimized for convective transfer has been shown to reduce the system's overall weight and thermal resistance, expanding design possibilities in space-constrained areas like data centres and aircraft cabins.

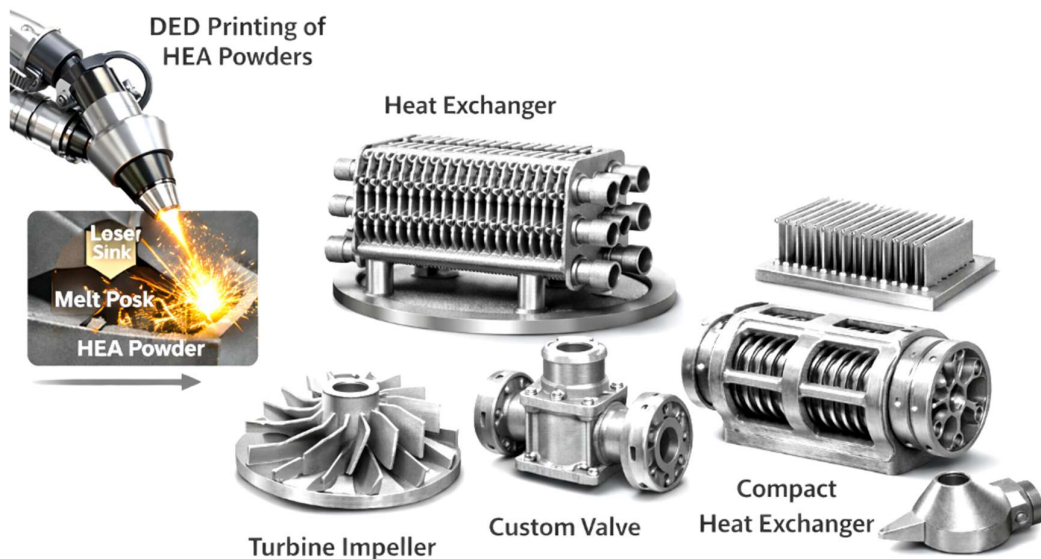


Fig. 6. 3D printed heat exchangers

3.2.2. Material savings

Additive manufacturing builds components layer by layer, maximizing the usage of raw materials and significantly reducing scrap compared to subtractive machining. For HEAs, which can be more expensive than conventional alloys, minimizing material waste becomes a critical economic advantage.

- near-net-shape production: by depositing or fusing only the required amount of HEA powder or wire, manufacturers avoid the large-scale removal of material inherent in milling or turning;

- reduced stock requirements: complex parts no longer need to start from bulky forgings or cast billets, leading to lower inventory and logistical costs [14].

This approach is especially helpful in HVAC, where customization (e.g., specialized fan blades or custom duct adaptors) often results in significant scrap if produced via traditional methods.

3.2.3. Enhanced mechanical properties

During many powder-bed or directed energy deposition processes, the rapid solidification of metal feedstock can yield fine-grained microstructures, resulting in enhanced mechanical performance [15]. In the context of HEAs, which already exhibit high strength and excellent durability, this phenomenon can further improve:

- tensile strength: HEA components fabricated via selective laser melting (SLM) or electron beam melting (EBM) have shown increased yield and ultimate tensile strength due to grain refinement [16];
- fatigue resistance: the fine microstructure may also limit the propagation of microcracks, translating to superior fatigue life under repeated loading conditions often encountered in HVAC fans and compressors;
- thermal stability: many HEAs maintain phase stability and structural integrity at elevated temperatures, further enhanced by the uniform as-built microstructure formed during rapid cooling [17].

4. Benefits and challenges in HVAC applications

HEAs have garnered significant attention in heating, ventilation, and air conditioning (HVAC) systems due to their formidable mechanical properties, corrosion resistance, and thermal stability. When paired with additive manufacturing (AM) methods (e.g., selective laser melting (SLM), directed energy deposition (DED)), these alloys promise longer service lives, improved performance, and cost-saving advantages. Figure 3 provides a conceptual illustration of the synergistic benefits HEAs and 3D printing offer for HVAC applications.

4.1. Benefits

4.1.1. Extended lifespan

One of the most significant advantages offered by HEAs in HVAC is extended component lifespan. These alloys owe their longevity to:

- intrinsic corrosion resistance: HEAs often develop protective oxide layers that inhibit corrosion processes, especially in moist or chemically aggressive HVAC environments [9, 13];
- thermal fatigue resistance: high configurational entropy helps stabilize microstructures against temperature fluctuations, reducing the likelihood of cracks and failures over repeated cycles [6, 7];

- additive design optimization: with AM, engineers can tailor part geometries - e.g., lattice structures or reinforced ribs - to distribute stress more evenly, thus minimizing structural weaknesses and extending service life [14].

By leveraging these attributes, HVAC components (e.g., fan casings, heat exchanger tubes, rotating shafts) stand to benefit from longer operational intervals and decreased failure rates.

4.1.2. Improved performance

In HVAC systems, overall efficiency and throughput can hinge on factors such as heat transfer and energy consumption. 3D-printed HEAs address these areas in multiple ways:

- customized heat exchanger designs: complex internal channels and intricate fins created via SLM or EBM maximize heat transfer surface area, resulting in improved thermal efficiency [15];
- lightweight and robust fan blades: advanced topology optimization combined with the high strength-to-weight ratio of HEAs fosters lighter, stronger rotating components. Lighter fans consume less energy and can reduce vibration, extending bearing life and improving reliability [16];
- enhanced flow dynamics: by incorporating streamlined contours or integrated fluid guides in conduits and ducts, airflow can be optimized, decreasing energy losses and improving overall handling capacity.

These features collectively contribute to reduced power consumption, lower operational costs, and fewer system downtimes, all of which are crucial in large-scale installations like data centres, hospital HVAC systems, or manufacturing plants.

4.1.3 Cost savings

While initial investments in 3D printing systems, HEA powders, and process development can be significant, the long-term economic benefits often justify these expenditures [9, 14]. Key cost-saving mechanisms include:

- reduced maintenance: DED is particularly valuable for repairing worn or damaged HEA components. Rather than scrapping an entire unit (e.g., a corroded fan hub or damaged heat exchanger plate), targeted deposition allows in-situ restoration [9, 17]. This practice can dramatically lower lifecycle costs and extended the useful life of essential HVAC hardware;
- minimized downtime: less frequent component failures translate to fewer unplanned shutdowns, which can be enormously costly in critical facilities;
- optimal material utilization: additive processes inherently minimize waste by depositing material only where it is needed, proving especially beneficial for expensive HEA feedstocks [14].

Together, these factors can significantly offset the higher upfront costs of implementing 3D-printed HEAs in HVAC, culminating in greater overall economic viability - particularly for mission-critical systems where reliability and efficiency are paramount.

4.2. Challenges

Despite the promising benefits of 3D-printed high-entropy alloys (HEAs) in HVAC systems, several challenges must be addressed before these advanced materials can be widely adopted. These obstacles range from supply-chain issues and cost considerations to process control and standards development. The following subsections detail the most common hurdles and provide insights into ongoing research and industry efforts aimed at overcoming them.

4.2.1. *Material cost and availability*

Although HEAs are gaining momentum in aerospace, energy, and other high-demand markets, cost and availability remain significant barriers:

- powdered feedstock: high-quality HEA powders tailored for specific AM processes (e.g. SLM, DED) can be expensive due to complex production routes (e.g., gas atomization) and limited-scale supplies [14];
- economies of scale: the relatively low demand for HEA powders - compared to conventional metals like stainless steel or aluminium - means they are not yet produced in large volumes, which inflates costs further;
- supplier network: a robust supply chain featuring multiple powder producers is needed to drive down prices and standardize quality. Many HVAC manufacturers, however, lack established procurement channels for high-entropy alloy materials [9].

Over time, as AM use cases continue to expand and HEA compositions are optimized for specific applications, economies of scale may reduce costs, enhancing feasibility for the HVAC sector.

4.2.2. *Complex process parameters*

Additive manufacturing of HEAs requires precise control of multiple process variables - a challenge that intensifies when dealing with highly reactive or multi-component metals:

- laser power and energy density: if power levels are too low, lack of fusion or porosity may result; if too high, spatter or excessive vaporization can occur [10];
- scanning speed and hatch distance: subtle changes in scan strategy can shift the thermal history and microstructural evolution of the alloy;
- build temperature: maintaining a uniform build environment is crucial to minimize thermal gradients that can lead to cracking or distortion.

Failure to optimize these parameters can yield undesirable phases, residual stress, or inconsistent microstructure, thus compromising mechanical strength, ductility, and corrosion resistance.

Modelling tools and in-situ monitoring systems are increasingly used to adjust process settings in real time, improving overall build quality and repeatability [15, 16].

5. Prospective developments and future directions

The integration of high-entropy alloys and additive manufacturing in HVAC applications opens up exciting possibilities for advanced materials and innovative engineering solutions. As research in this area expands, the next phase of developments will likely address design optimization, standardization, cost reduction, smart monitoring, and multi-functional materials. Below are the primary future directions that promise to enhance the viability and performance of 3D-printed HEAs in the HVAC industry.

5.1. Design optimization tools

Recent progress in computational modelling and topology optimization aims to exploit the unique mechanical and thermal properties of HEAs:

- advanced simulation: techniques such as finite element analysis (FEA) and computational fluid dynamics (CFD) allow precise prediction of heat transfer, stress distribution, and flow patterns in material designs [18];
- AI-assisted optimization: machine learning algorithms can rapidly evaluate microstructure – property relationships, suggesting ideal compositions or fabrication parameters for custom HVAC parts [19];
- generative design: tools like Autodesk Generative Design and Siemens NX offer capabilities for lightweighting, lattice structures, and complex geometries, building on HEA mechanical robustness to develop novel part designs with unprecedented performance.

As these software tools gain maturity, they will rapidly accelerate the design – build – test cycles, enabling more efficient and innovative HVAC component solutions.

5.2. Cost reduction and supply chain improvements

Although HEA powders can be expensive, cost reduction and supply chain enhancements will likely expand the commercial viability of HEAs in HVAC:

- economies of scale: increased demand for HEAs in aerospace, energy, and automotive sectors enhances bulk production, leading to lower unit costs [14, 22];
- consolidated supply chains: collaboration between material suppliers, AM system manufacturers, and end-users in HVAC can coordinate R&D and production efforts, ensuring consistent powder availability and quality;
- new alloy development: research into lower-cost HEA ingredients (e.g., partially replacing expensive Co or Ni with abundant elements) can also reduce overall material expense without sacrificing core performance [19].

By addressing material economies, standardization, and logistics, HEAs will become increasingly attractive for HVAC applications requiring durable, high-performance alloys.

5.3. Smart monitoring and digital twins

Integrating Internet of Things (IoT) sensors and digital twin technologies offers real-time insights into component health and operational performance:

- predictive maintenance: sensor networks embedded in 3D-printed HEA parts can continuously monitor stress, temperature, vibration, and corrosion indicators. Advanced data analytics or machine learning can forecast failure modes, ensuring timely maintenance actions;
- digital twins: virtual replicas model physical HVAC systems through continuous data feeds, enabling simulation of how HEA components degrade or react under certain thermal or mechanical loads [23];
- targeted DED repair: based on sensor feedback, directed energy deposition can be initiated only where and when needed, minimizing downtime and extending service life.

These cyber-physical systems are the next level of proactive maintenance, offering cost-saving strategies while further enhancing the reliability of HEA-based HVAC systems.

5.4. Multi-functional materials

As the frontier of materials research expands, combining HEAs with other material systems may yield hybrid structures possessing unusual or next-level performance attributes:

- ceramic or polymer composites: embedding ceramic phases in HEA matrices could augment thermal insulation or wear resistance. Similarly, polymer over moulding might enable noise damping or vibration control in rotating assemblies [24];
- functional gradients: by additively blending multiple feedstock materials (e.g., metal-ceramic transitions), components can be graded to tailor thermal conductivity, stiffness, or coefficient of thermal expansion [25];
- surface coatings: functionally graded or co-deposited coatings may offer improved surface hardness, chemical barrier properties, or anti-fouling characteristics particularly beneficial in humid or chemically volatile HVAC conditions.

Such multi-functional combinations promise to deliver thermal, acoustic, and mechanical enhancements far beyond those of current single-alloy approaches, broadening the potential for HEAs in extreme or specialized HVAC environments.

6. Conclusions

3D-printed high-entropy alloys (HEAs) are rapidly emerging as a key enabling technology for the next generation of HVAC systems. By combining the intrinsic advantages of HEAs - such as superior corrosion resistance, thermal fatigue strength, and mechanical robustness - with the unprecedented design freedom of additive manufacturing (AM), engineers can produce highly optimized heat exchangers, fan blades, and airflow conduits that meet stringent energy efficiency and durability requirements [9, 14]. In addition, directed energy deposition (DED) offers cost-effective repair strategies, reducing material waste and maintenance downtime while extending the operational life of critical HVAC components [9].

However, realizing the full potential of 3D-printed HEAs in HVAC applications entails addressing several challenges. These include high powder costs driven by limited commercial production, complex process parameters requiring precise control, and the need for improved standardization to ensure consistent quality and regulatory acceptance [14, 21]. As the field progresses, collaborative efforts among material suppliers, research institutions, HVAC manufacturers, and standards organizations will be essential to drive down costs, streamline process control, and develop standardized testing and certification protocols [20, 21].

Looking to the future, sustained research and targeted investments are expected to accelerate advancements in computational modelling, topology optimization, powder production scalability, and real-time process monitoring. These developments will further enhance the mechanical, thermal, and economic viability of HEAs and spur broader adoption of AM-enabled solutions in high-demand HVAC environments. Ultimately, 3D-printed HEAs have the potential to revolutionize how HVAC systems are designed, manufactured, and maintained, ushering in an era of greater energy efficiency, longer service life, and reduced lifecycle costs for critical building infrastructure.

References

- [1]. Cantor, B., Chang, I. T. H., Knight, P., & Vincent, A. J. B. (2004). Microstructural development in equiatomic multicomponent alloys. *Materials Science and Engineering A*, 375-377, 213-218.
- [2]. Yeh, J. W. (2013). Alloy design strategies and future trends in high-entropy alloys. *JOM*, 65(12), 1759-1771.
- [3]. DebRoy, T., Wei, H. L., Zuback, J. S., et al. (2018). Additive manufacturing of metallic components - process, structure and properties. *Progress in Materials Science*, 92, 112-224.
- [4]. Miracle, D. B., & Senkov, O. N. (2017). A critical review of high entropy alloys and related concepts. *Acta Materialia*, 122, 448-511.
- [5]. Zhu, J., Feng, R., Lee, C., et al. (2019). Microstructure and mechanical behavior of high entropy alloys. *Materials Today*, 20, 55-62.
- [6]. Shi, Y., Yang, B., & Liaw, P. K. (2017). Corrosion-resistant high-entropy alloys: a review. *Metals*, 7(2), 43.
- [7]. Schuh, B., Mendez-Martin, F., Völker, B., et al. (2015). Mechanical properties and thermal stability of a nanocrystalline CoCrFeMnNi high-entropy alloy after severe plastic deformation. *Acta Materialia*, 96, 258-268.
- [8]. Miao, J. W., & Tsai, C. W. (2017). Wear behavior of high entropy alloys. *Wear*, 376-377, 585-592.
- [9]. Li, N., Wu, Q., Jiang, B., et al. (2019). Directed energy deposition of high entropy alloys: characterization, properties and applications. *Materials & Design*, 182, 108065.
- [10]. Thijs, L., Kempen, K., Kruth, J. P., & Van Humbeeck, J. (2013). Fine-structured aluminium products with controllable texture by selective laser melting of pre-alloyed AlSi10Mg powder. *Acta Materialia*, 61(5), 1809-1819.
- [11]. Al-Bermani, S. S., Blackmore, M. L., Zhang, W., & Todd, I. (2010). The origin of microstructural diversity, texture, and mechanical properties in electron beam melted Ti-6Al-4V. *Metallurgical and Materials Transactions A*, 41(13), 3422-3434.
- [12]. Carroll, B. E., Otis, R. A., Borgonia, J. P., et al. (2016). Functionally graded metal components made via directed energy deposition: Microstructure and metallurgical considerations. *Materials Science and Engineering: A*, 696, 128-134.
- [13]. Yang, S., & Zhao, Y. F. (2015). Additive manufacturing-enabled design theory and methodology: a critical review. *The International Journal of Advanced Manufacturing Technology*, 80(1), 327-342.
- [14]. Frazier, W. E. (2014). Metal additive manufacturing: a review. *Journal of Materials Engineering and Performance*, 23(6), 1917-1928.

- [15]. Gu, D., Meiners, W., & Poprawe, R. (2014). Laser additive manufacturing of metallic components: materials, processes and mechanisms. *International Materials Reviews*, 59(3), 114-135.
- [16]. Li, Z., Raabe, D., & Ma, D. (2019). Design of high entropy alloys: From bulk to thin films and coatings. *MRS Bulletin*, 44(10), 779-787.
- [17]. Wu, Q., Feng, R., Lee, C., et al. (2020). Microstructure and high temperature properties of a high entropy alloy processed by selective laser melting. *Materials & Design*, 192, 108758.
- [18]. Liu, Z., Guo, J., & Jin, M. (2021). Topology optimization of an additively manufactured high-entropy alloy bracket for aerospace applications. *Aerospace Science and Technology*, 117, 106914.
- [19]. Li, Z., Raabe, D., & Ma, D. (2019). Design of high entropy alloys: From bulk to thin films and coatings. *MRS Bulletin*, 44(10), 779-787.
- [20]. Varalakshmi, S., Kamat, S. V., & Sharma, R. K. (2021). Development and characterization of high entropy alloys for marine applications. *Transactions of the Indian Institute of Metals*, 74(2), 417-429.
- [21]. ISO/ASTM 52900-15. Standard terminology for additive manufacturing - General principles - Terminology. ASTM International, West Conshohocken, PA, and ISO, Geneva, Switzerland.
- [22]. Hemphill, M. A., Yuan, T., Wang, G., et al. (2015). Fatigue behavior of high-entropy alloys. *Acta Materialia*, 112, 403-411.
- [23]. Madni, A. M., Madni, C. C., & Lucero, S. D. (2019). Leveraging digital twin technology in model-based systems engineering. *Systems*, 7(1), 7.
- [24]. Chen, J. Y., Zhang, S., & Zhang, Z. (2022). Hybrid composites of high-entropy alloys and ceramics for high-temperature applications. *Journal of Alloys and Compounds*, 907, 164498.
- [25]. Shi, Y., Zhang, Y., & Liaw, P. K. (2017). Microstructures and properties of high-entropy alloy coatings and claddings. *Journal of Alloys and Compounds*, 698, 778-784.

State of the art of rebars problem in 3D printing of concrete in construction

Stadiul actual al soluțiilor de armare în imprimarea 3D a betonului în construcții

Hicham Bensafi¹

¹ Technical University of Construction Bucharest
Bulevardul Lacul Tei 124, București 020396, Romania
E-mail: bns.hicham41@gmail.com

DOI: 10.37789/rjce.2026.17.3.17

Abstract. *Construction advances in 3D concrete printing boost design freedom, but reinforcement bars present obstacles. Incompatibility with 3D printing, positioning and accuracy issues, concrete adhesion issues, synchronization issues, and corrosion and fractures are major obstacles. To solve these problems, the use of fiber and other methods is necessary. Digital control and robotics improve printing accuracy, but the lack of standards makes study validation and comparability difficult. Since present techniques weaken automation and structural strength, rebar integration must be addressed. To improve 3D concrete printing, future research must combine materials science, mechanics, and robotics.*

Keywords. 3D concrete printing, reinforcement bars, Incompatibility, rebar integration

1 Introduction

Additive manufacturing (3D printing) has become popular across industries for its capacity to build complicated goods through bespoke designs and layer-by-layer procedures. As digitization advances, the construction industry has widely utilized AM technologies, especially 3DCP. [1] Concrete is a popular building material due to its compressive strength and adaptability. Energy-absorbing and ductile structural uses are limited by its brittleness and low tensile strength (TS). Reinforcement materials, especially steel bars, were recommended in the 19th century to overcome these restrictions. Steel's strong ductility and concrete-like heat coefficient increase tensile capacity and prevent bond failure. [2]

The article was received on 04.07.2026, accepted on 11.09.2026 and published on 22.09.2026

Due to its anisotropic nature, 3D printed concrete needs reinforcement to ensure structural stability and integrity. [3] Current reinforcement methods for layer-by-layer printed concrete buildings cannot incorporate continuous vertical reinforcements, impacting structural integrity. Researchers are investigating methods that partially meet integrity criteria or supplement concrete printing. Vertical reinforcements injected during printing or post-installation, horizontal reinforcements extruded or put on printed layers, and reinforcement cages in printed formworks are proposed. [4]

The difficulties of integrating traditional rebar reinforcement into printed concrete structures hinders 3D Concrete Printing (3DCP). Manual steel reinforcement installation was laborious and unautomated in previous efforts. Continuous steel cables and 3D printed rebar offer little structural improvement over regular rebars. Thus, automating concrete printing and rebar integration remains difficult. [5]

Despite the importance of reinforcing, 3D-printed concrete structures with conventional steel bars are more complicated than traditional concrete buildings. [3] 3D printing's layer-by-layer deposition can disrupt rebar placement, weakening the bond and perhaps causing concrete slippage. [6] The goal is to create and apply 3D-printed concrete in construction, addressing technical obstacles using sophisticated reinforcement technologies. [7] Steel bars, especially when paired with other materials, can improve structural integrity through novel bidirectional steel mesh arrangements. [8]

2.Technologie

2.1 rebars problem and solved with fibers or other technic

2.1.1 Incompatibility of reinforcement bars with the printing 3d concrete process

3D-printed concrete is growing in research and business, but it lacks internal reinforcement. FRP reinforcement improves 3D printed concrete, but traditional production procedures limit on-site use. ZENG et al. use continuous fiber reinforced thermoplastic polymer (CFRTP) to create a 3D-printed concrete reinforcement (Fig 1). A study examined the tensile performance of 3D printed CFRTP bars and grids, then tested twenty-two concrete plates to see how loading direction and manufacturing type affected their flexural behavior. Performance is greatly improved with FRP reinforcement, with CFRTP reinforcement performing similarly. ZENG et al. recommend CFRTP reinforcement research to improve 3D printed reinforced concrete structures that blend concrete and FRP reinforcement (Fig 2). [1]

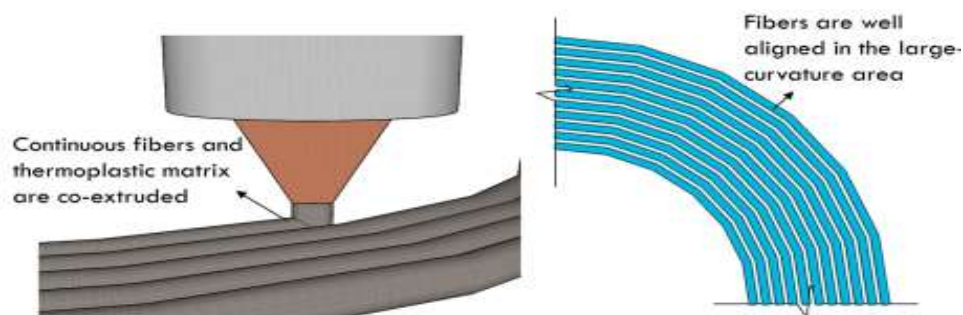


Fig 1 Continuous fiber reinforced thermoplastic polymer based on additive manufacturing. [1]

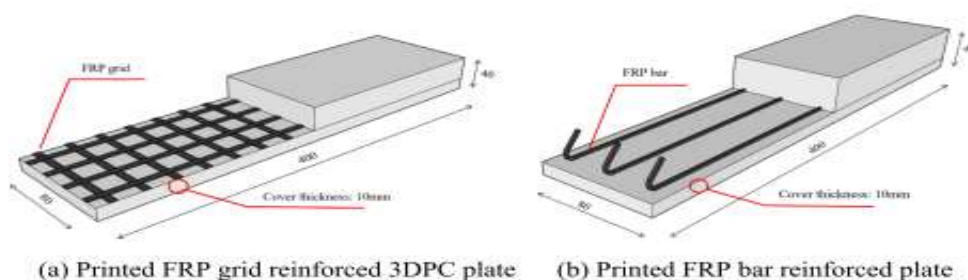


Fig 2 Schematic illustration of specimens. [1]

Due to environmental, resource, and economic considerations, AMIRTHARAJ et al. recommend alternate construction materials. Following IS and ASTM standards, they compare the mechanical characteristics of GFRP, CFRP, BFRP, and bamboo bars to steel. FRP bars fulfill strength standards but not the 200 GPa modulus standard with tensile strengths of 640 to 2136.9 MPa and elastic moduli of 34.2 to 140 GPa. Although pricey, stainless steel fits both criteria with strengths of 764–1116 MPa and moduli of 141–202.6 GPa. 250.3–370 MPa Bamboo tensile strength and 5.5–27 GPa moduli limit it to non-structural uses. FRP beams have equal ultimate loads to steel but more deflection and breaking. The research emphasizes the necessity for alternative steel bars that match structural performance and standard standards. [2]

SALAIMANIMAGUDAM et al. use CRITIC objective weighting, MABAC, and SAW multi-criteria decision-making to study reinforcing inclusion strategies for 3D-printed concrete structures. No reinforcement, conventional, micro, post-tensioned, and sync reinforcement are tested for automation, integration, time, and structural effectiveness. Automation and structural efficacy affect decision-making, with conventional reinforcement preferred above micro and sync reinforcement. The research warns against utilizing 3D-printed concrete without reinforcement due to poor structural performance and emphasizes computerized post-tensioned strengthening to increase structural integrity and efficiency (Fig 3). [3]

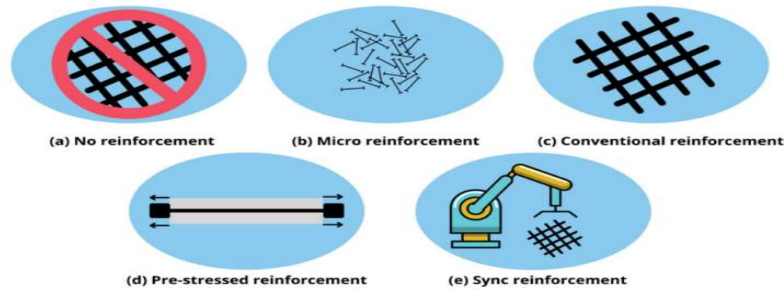


Fig 3 Types of Reinforcement Incorporation Method [3]

According to WANG et al. 3D printed concrete truss structures are lightweight and easy to manufacture, but reinforcement-concrete interfacial incompatibility affects structural dependability. Innovative 3D conical reinforcement improves load transfer efficiency and mechanical behavior. Performance of planar reinforcement ratio, conical reinforcement design, and shear-span ratio was tested on 10 beams. Compared to 2D techniques, final shear capacity increased 15% and post-peak deformation 40%. built updated finite element models to describe load transmission processes and a modified shear capacity calculation model that matched experimental results (Fig 4). [4]

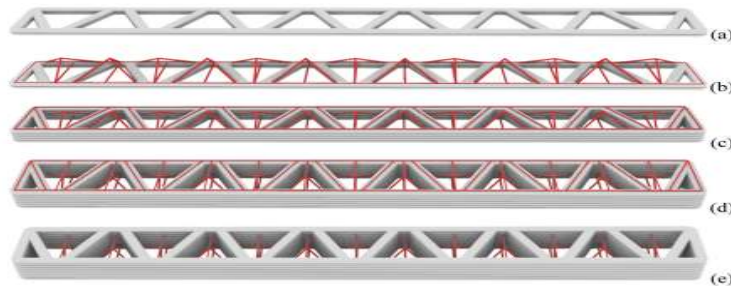


Fig 4 Key steps of 3D conical rebars reinforced 3DPC beam: (a) Print bottom concrete; (b) Lay 3D conical reinforcement; (c) Lay 2D truss reinforcement as needed; (d) Lay top 2D truss reinforcement and spot weld; (e) Print top concrete. [4]

Although 3D printing concrete (3DCP) promises more sustainability and productivity, automating the incorporation of rebar reinforcement presents difficulties (Fig 5). To address these challenges, DU et al. provide an automated robotic system in conjunction with Building Information Modeling (BIM) (Fig 6). They created a deep learning model and used Dynamo scripts to create printing routes that were optimized for rebar integration. The model achieved 92.5% accuracy in rebar recognition with a 2 mm location inaccuracy. The first real-world example of an automated system combining rebar with printed constructions utilizing BIM data was made possible by a centralized control system that allowed communication between gadgets like a camera and a robot arm. [5]



Fig 5 Experimental setup. (a) Gripper; (b) Concrete extruder; (c) Rebars and printing base. [5]

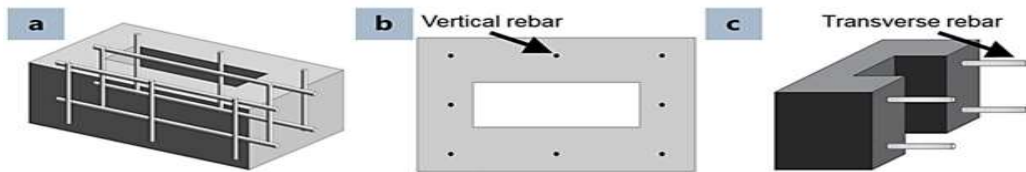


Fig 6 BIM model. (a) 3D view; (b) Top view; (c) Cross section view. [5]

Rebars and 3D concrete printing (3DCP) are incompatible because to bonding issues, reinforcement integration issues, and interface structural faults. Lack-of-fusion (LOF) in printed layers affects 3D printed concrete with integrated rebars structural integrity and performance.

3.2.2 positioning and accuracy of reinforcement bars in 3D concrete printing in construction

Digital construction production might benefit from 3D Concrete Printing (3DCP), but a lack of structural performance data hinders its use. Mechanical performance depends on reinforcement placement in printed layers and toolpath methods on concrete characteristics (Fig 7). LIU et al. study 3DCP beam flexural behavior with different reinforcement locations and toolpath techniques. Toolpath orientation perpendicular to reinforcement reduces shear and delamination failures and promotes flexural cracking, therefore it may be ignored. Steel reinforcement near the upper layers performs better flexurally than reinforcement toward the bottom (Fig 8). [9]



Fig 7 3D printed concrete beams process: a) printing of bed-surface layers b) placement of steel rebars c) printing of encasement layers. [9]



Fig 8 Three-point bending test of steel rebar reinforced concrete beams for a) rebar placed at bottom (TP||-Bar@layer3 and TP⊥-Bar@layer3) and b) rebar placed at top (TP||-Bar@layer6 and TP⊥-Bar@layer6). [9]

Due to its lightweight and quick manufacturing, reinforced 3D printed concrete (3DPC) truss structures are becoming popular load-bearing systems. Unfortunately, their reinforcing design and structural performance are little understood. The WANG et al. process includes topology optimization, reinforcement design, and structural performance assessment for 3DPC truss beams to improve design approaches (Fig 9). This technique optimises tension and compression struts for weight reduction and stress transmission depending on printing limits. Stress flow analysis determines reinforcement that makes unreinforced trusses load-bearing and ductile. Tests and finite element model simulations show that topology optimized 3DPC truss beams may increase strength-to-weight ratio by 94% while retaining failure deflection-to-weight ratios equivalent to reinforced concrete beams (Fig 10). [10]

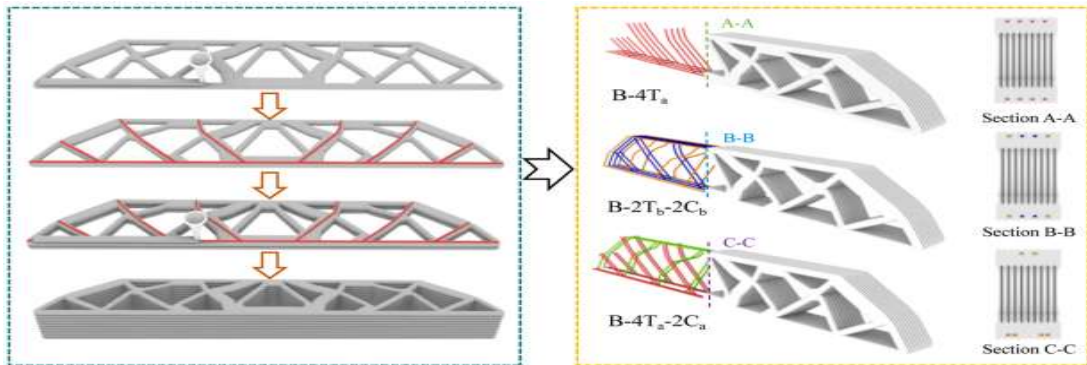


Fig 9 Specimens fabrication process and design. [10]



Fig 10 Reinforcement placement for different configurations. [10]

In 3D concrete printing, automation and structure integration are key problems for reinforcement bar positioning. An autonomous robot system uses BIM to generate paths and a deep learning model to recognize rebar. [5]

Reinforcement bar integration in 3D concrete printing (3DCP) involves placement, bonding, and automation issues. These challenges must be addressed to improve printed component structural integrity and performance.

3.2.3 Limited adhesion between steel and printed 3d concrete in construction

LIU et al. describe spray-based 3D (S-3D) concrete printing method for synchronous reinforced concrete construction. Reinforcement is included into S-3D printed 2.5D rebar concrete design by the authors. They found that 2.5D rebar mesh improves early stiffness, ductility, strain propagation, and ultimate load capacity of printed concrete slabs by 19.04%–81.12% compared to 2D mesh. This approach proves S-3D printing reinforcement and automates large-scale rebar concrete buildings(Fig 11). [6]

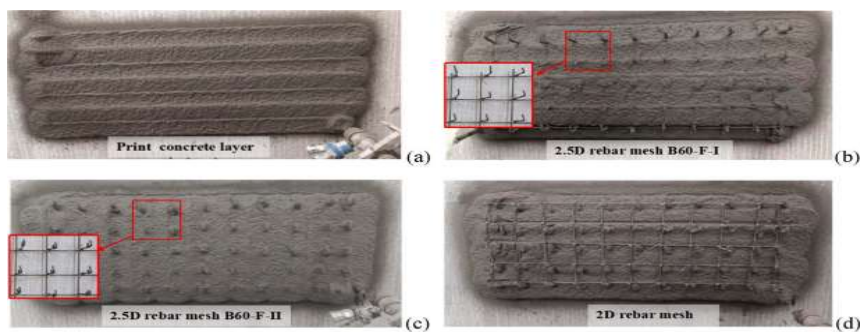


Fig 11 Process of printed concrete slabs with different types of hooks. [6]

SHAHZAD et al. used a validated finite element model to study steel reinforcing bar pull-out in 3D-printed concrete (3DPC). The study examines concrete-to-concrete contacts' peak load, slide behavior, failure causes, and damage criteria. Mold-cast

specimens had a 9.38% greater load-bearing capacity than interlayer and 25% above interstrip 3D printed specimens, while 3DPC has lower starting stiffness. Print angle decreases from 0° to 30° and increases to 90° , when peak load is highest. For stress concentrations, specimens at 30° have the most damage, while those at 90° have the least. Peak load capacity increases with layer size, and specimens with a 50 mm bond length perform best, providing valuable insights for future 3DPC modeling of concrete surfaces (Fig 12). [11]

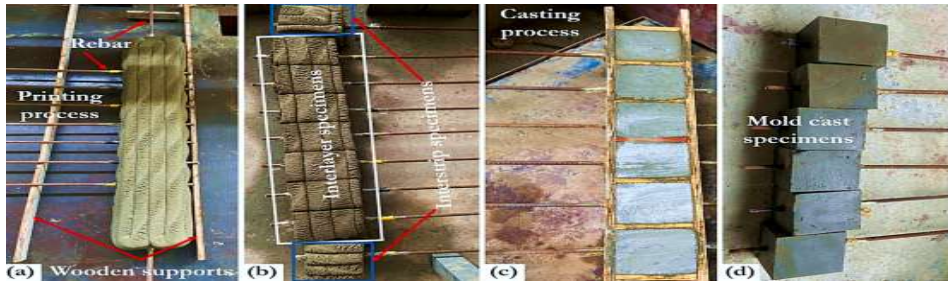


Fig 12 Printing and casting of specimens: (a) 3D printing and rebar placing process; (b) 3D-printed specimens; (c) casting of mold cast specimens; and (d) mold-cast specimens. [11]

According to CAO et al., 3D-printed concrete without reinforcements, especially vertical reinforcement, is problematic. They recommended injecting high-flowability material to join reinforcement segments to build a mortar reinforcing mesh in-situ (Fig 13). This flexural testing method used parallel and interlaced epoxy-coated steel fibers in beams. In-situ mesh outperformed independent reinforcements in flexural strength by 123.6%. The high-flowability epoxy filled concrete gaps during fabrication, proving multi-directional reinforcement integration in 3D-printed concrete structures and the practicality of 3D printing (Fig 14). [7]

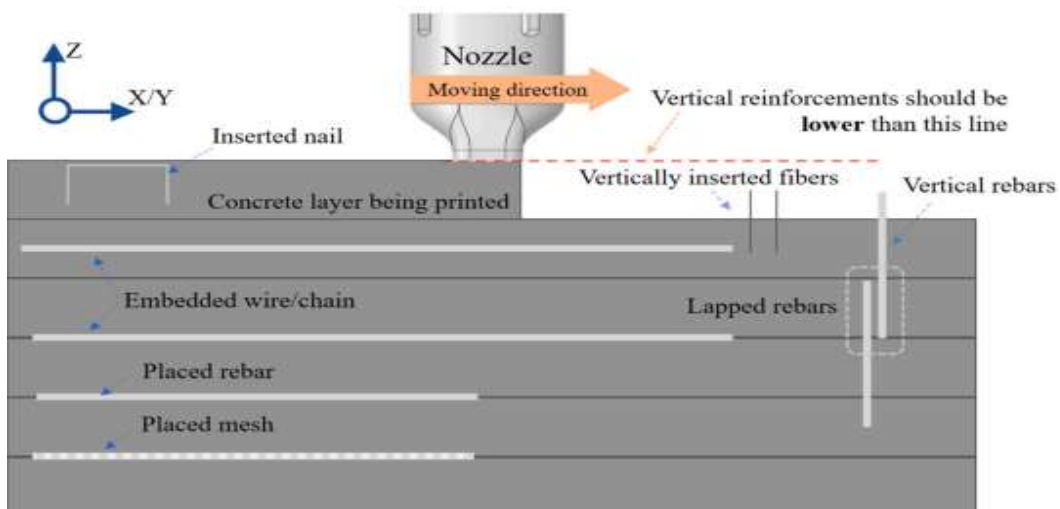


Fig 13 Current post-reinforcing techniques and reinforcement positions [7]

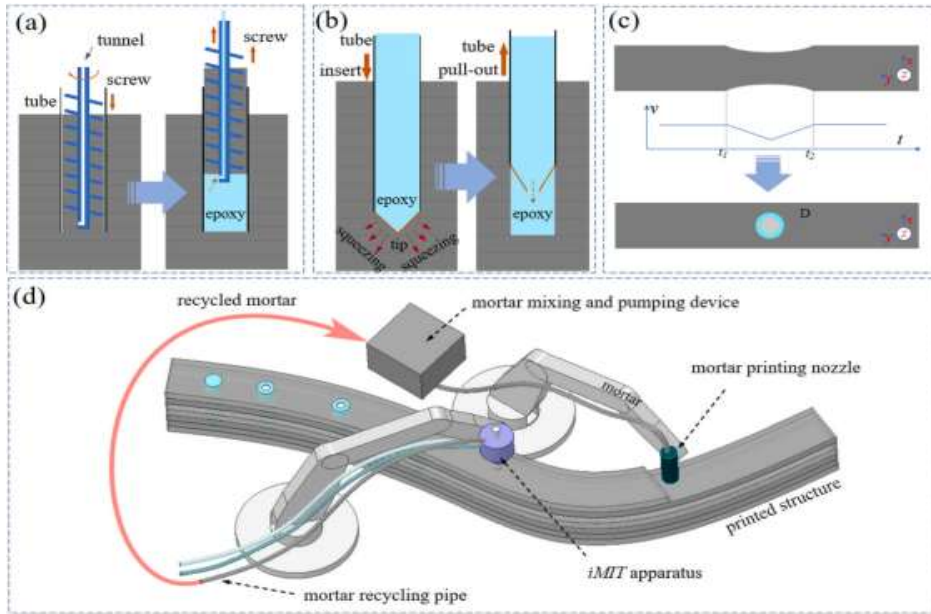


Fig 14 Illustration of the hybrid printing and reinforcing system. (a) tube insertion method, (b) mortar dispersing method, (c) mortar geometry control, and (d) demonstration of the mortar dispersion and recycling. [7]

Mechanical and chemical interactions at its contact limit steel-printed 3D concrete adherence in building. This is crucial for improving the performance and longevity of hybrid structures incorporating both materials.

3.2.4 Difficult synchronization between printing and rebar in 3d printing concrete in construction in construction

Steel cable bonding in fresh mortar and 3D printed beam flexural behavior.

LIU et al. use steel wires in printed mortar strips to enhance concrete printing path-following. They tested mortar bonding with 0.5 mm, 1 mm, and 1.5 mm steel cables using pull-out and four-point bending (Fig 15). 0.5 mm and 1 mm cables maintained buildability within open-time restrictions, while 1.5 mm cables bounced off the mortar, impairing reinforcing feasibility. Bonding strength was 1.4–2.4 MPa, lower than concrete reinforcement. Flexural strength increased up to 90%, and ductile fracture modes were detected. This method shows that 3D printing can improve reinforcing methods (Fig 16). [12]

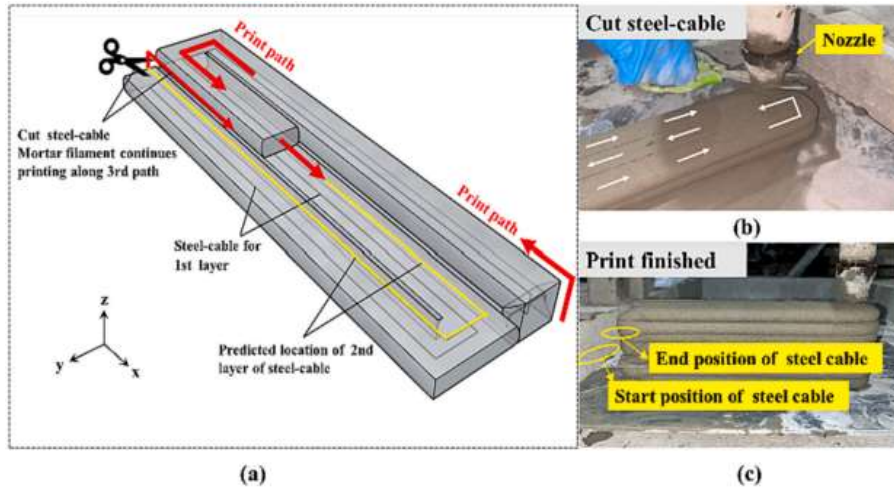


Fig 15 Print Path Schematic for four-point bending test specimen (a) Printing path; (b) Cut steel cable; (c) Finish printing [12]

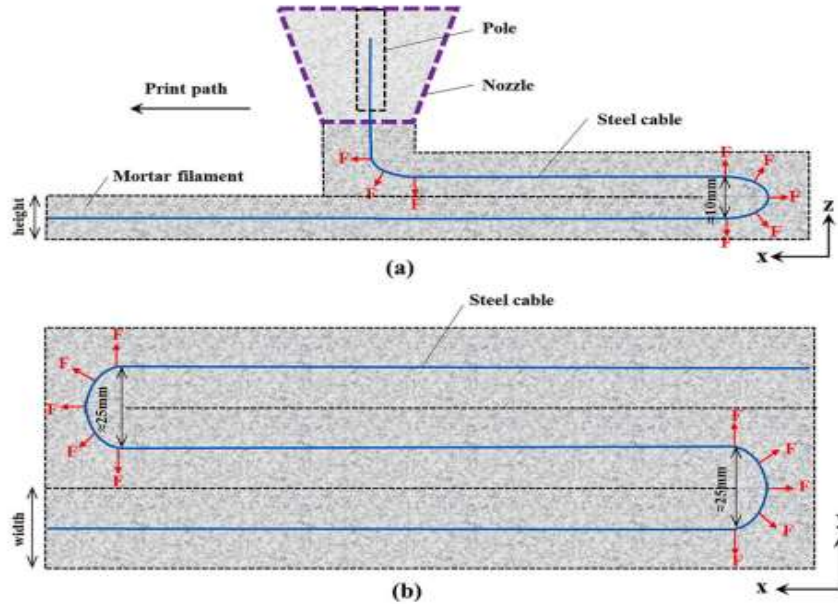


Fig 16 Schematic of bending resilience of steel cable at turns in print path (a) xoz plane; (b) xoy plane [12]

The buildability and flexural properties of 3D printed recycled mortar reinforced with synchronized steel cable under different reinforcement ratios.

LIU et al. used 30% recycled sintered brick powder in their mixture and modified their printing apparatus to enable synchronized reinforcing of 3D printed mortar with steel cables (Fig 17). It was discovered that the ideal range for open time was 10 to 40 minutes. About 2 to 2.5 MPa of binding strength existed between the cables and mortar. Multiple fractures appeared at mid-span during failure, and flexural strength saw a rise of 172%

to 357 percent. Within a 12% inaccuracy of test data, a flexural strength adjustment formula produced results(Fig 18). [13]

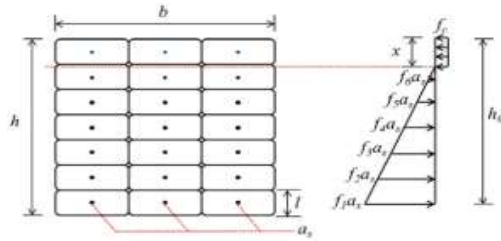


Fig 17 The stress diagram of the bending section. [13]

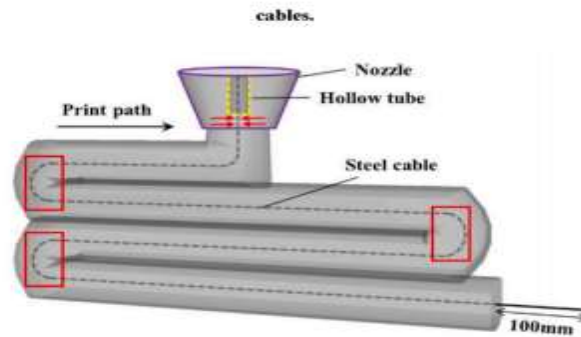


Fig 18 Schematic diagram of steel cable reinforcement printing process (red wireframe shows anchoring formed by steel cable at turning and climbing). [13]

In 3D concrete printing, rebar placement and printing synchronization affect structural integrity and efficiency. The ultimate structure's performance depends on the incorporation of reinforcement materials.

3.2.5 Rebar durability problems (corrosion, coating, fractures) in 3D-printed concrete for building.

Steel bars in reinforced concrete corrode in severe situations, reducing structural longevity. Using a phase field technique (PFM), YUAN et al. examine how corrosion morphology, cover thickness, concrete strength, heterogeneity, steel bar diameter, and aggregate content affect concrete damage. They found that corrosion morphology and concrete heterogeneity considerably impact durability and damage susceptibility. Concrete strength has little influence, although lesser strength increases cover failure risk. Cover thickness and steel bar diameter hardly affect durability and failure. While aggregate content does not correlate with longevity, aggregate distribution greatly affects it. For concrete structure engineering and durability evaluation, the study provides crucial information. [14]

ZHANG et al. report that concrete 3D printing is a major technology in the construction industry's focus on digitalisation and sustainability. The durability of 3D printed cement-based materials (3DPCM) remains unknown, preventing its usage in load-bearing constructions. [15] ZHANG et al. tested 3DPCM durability in 15 labs in 13 countries for water absorption, carbonation, and chloride intrusion. Water absorption tests show bulk porosity, whereas carbonation and chloride tests show local flaws (Fig 19). Cast samples had more water penetration than ordinary concrete, but equivalent carbonation and chloride resistance. Anisotropy hampered 3DPCM longevity, although better mixture design and processing helped. Carbonation depth measurements revealed cold connections in three cross-section geometries due to printing variations. We also suggested methodological changes for future study. [15]



Fig 19 Sacrificial anodic cathodic protection structure schematic [15]

WANG et al. claim that corrosion of steel rebar shortens the lifespan of reinforced concrete structures and poses a safety concern to structural engineering. The research examines passivation and corrosion mechanisms, focusing on chloride ion penetration and concrete carbonization. It suggests methods for extending concrete's lifespan, such as strengthening protective coatings and rebar's resistance to corrosion. The research also describes required corrosion testing methodologies and uses X-CT to analyze steel bar corrosion byproducts and interfaces. It emphasizes corrosion studies and microstructural qualities and suggests further study. [16]

TAHERI-SHAKIB et al. study how pit distribution influences concrete pore architecture and crack propagation during galvanostatic accelerated corrosion. One sample had bigger, scattered pits, whereas the other had smaller, concentrated pits. X-ray CT, SEM, EDS, and Raman spectroscopy showed that bigger pits formed only iron hydroxides, while smaller pits formed both oxides and hydroxides. Crack patterns differed significantly: samples with dense pit distribution exhibited cracks from pore closeness to reinforcing bars and wider outward-diffusing cracks, whereas samples with less pits

had a different crack pattern. Also, elemental mapping showed increased corrosion product concentrations near fissures, suggesting water movement into the concrete matrix. These studies help improve infrastructure longevity by enhancing concrete degradation knowledge. [17]

According to CADENAZZI et al. rebars made of hemp fiber-reinforced polymer (HFRP) are a sustainable substitute for glass fiber-reinforced polymer (GFRP) and carbon steel (CS) in concrete reinforcement. After testing the mechanical properties and sustainability of HFRP rebars, the study concludes with a simulated tensile test that shows HFRP's tensile strength is superior to GFRP and on par with CS 235, but with somewhat less stiffness. Graphene fiber integration might improve mechanical properties. For applications requiring moderate strength and endurance, HFRP rebars are economical, lightweight, and environmentally benign. Large-scale production trials and long-term durability studies in challenging settings are required to support the use of HFRP rebars in infrastructure projects. [18]

ZHAO et al. emphasize the importance of selecting the right coating technology and ensuring quality control for effective anti-corrosion protection. China recommends two or three layers with defined kinds and thicknesses, whereas international standards are less specific. Long-term stability is improved by multilayer systems 82% chloride ion penetration resistance and 50% mass loss reduction from freeze-thaw cycles. Cross-border projects require standardized suggestions and quality control systems to increase coating technology applicability and dependability due to national standard differences. [19]

Conclusion

Innovation in materials for 3D concrete printing is revolutionizing the construction sector by improving productivity, offering greater architectural freedom, and enhancing durability. However, for this technology to become a reliable and widely adopted standard, it is essential to continue research on several critical aspects such as interlayer strength, durability, material reinforcement, mixture stabilization, and process standardization. Addressing these technical and scientific challenges is crucial to enable 3D concrete printing to evolve from an emerging technology to a fully mastered and sustainable solution for the future of buildings. This transition could transform not only construction methods but also the standards that underpin the modern construction industry.

Reference

- [1] ZENG, Jun-Jie, et al. 3D printing of FRP grid and bar reinforcement for reinforced concrete plates: Development and effectiveness. *Composite Structures*, 2024, 335: 117946.
- [2] AMIRTHARAJ, J.; ROSE, A. Leema. A state-of-the-art review on the Structural Behavior of concrete structures reinforced with various rebars as alternative to steel rebars. *Journal of Building Engineering*, 2025, 113387.
- [3] SALAIMANIMAGUDAM, M. P.; JAYAPRAKASH, J.; ANWAR, Mohammed Parvez. Selection of Reinforcement Incorporation Method for 3D Printed Concrete using MCDM. *Iranian Journal of Science and Technology, Transactions of Civil Engineering*, 2025, 1-13.
- [4] WANG, Li, et al. Design method and force transmission mechanism of 3D printed concrete truss beams reinforced with 3D conical reinforcement. *Engineering Structures*, 2025, 344: 121368.
- [5] DU, Song, et al. A BIM-enabled robot control system for automated integration between rebar reinforcement and 3D concrete printing. *Virtual and Physical Prototyping*, 2024, 19.1: e2332423.
- [6] LIU, Xiongfei; YANG, Xiaojie; SUN, Yuhang. Synchronous construction of spray-based 3D printed reinforced concrete structure: Effect of 2.5 D rebar structure on the flexural performance of slab. *Journal of Building Engineering*, 2025, 105: 112552.
- [7] CAO, Xiangpeng; WU, Shuoli; CUI, Hongzhi. Experimental study on in-situ mesh fabrication for reinforcing 3D-printed concrete. *Automation in Construction*, 2025, 170: 105923.
- [8] NAN, Bo, et al. Advancing Structural Reinforcement in 3D-Printed Concrete: Current Methods, Challenges, and Innovations. *Materials*, 2025, 18.2: 252.
- [9] LIU, Xingzi, et al. Factors affecting the flexural performance of reinforced 3D printed concrete beams. *Engineering Structures*, 2025, 337: 120497.
- [10] WANG, Qiang, et al. Reinforcement design and structural performance for the topology optimized 3D printed concrete truss beams. *Engineering Structures*, 2025, 332: 120064.
- [11] SHAHZAD, Qamar; LI, Fangyuan. Influence of concrete interfaces on the damage and pull-out behavior of 3D-printed concrete structures. *Engineering Failure Analysis*, 2025, 174: 109470.
- [12] LIU, Qiong, et al. Steel cable bonding in fresh mortar and 3D printed beam flexural behavior. *Automation in Construction*, 2024, 158: 105165.
- [13] LIU, Qiong, et al. The buildability and flexural properties of 3D printed recycled mortar reinforced with synchronized steel cable under different reinforcement ratios. *Journal of Building Engineering*, 2024, 84: 108484.
- [14] YUAN, Min, et al. Analysis of factors affecting structural durability based on reinforced concrete corrosion-induced cracking. In: *Structures*. Elsevier, 2025. p. 108677.
- [15] ZHANG, Yi, et al. Durability assessment of 3D printed cement-based materials: a RILEM TC 304-ADC interlaboratory study. *Materials and Structures*, 2025, 58.9: 314.
- [16] WANG, Qiuyue, et al. Research progress in corrosion behavior and anti-corrosion

methods of steel rebar in concrete. *Metals*, 2024, 14.8: 862.

[17] TAHERI-SHAKIB, Jaber; AL-MAYAH, Adil. Effect of corrosion pit distribution of rebar on pore, and crack characteristics in concrete. *Cement and Concrete Composites*, 2024, 148: 105476.

[18] CADENAZZI, Thomas; KELES, Busra. Advancing Sustainable Structural Solutions: Hemp Fiber-Reinforced Polymer (HFRP) Reinforcement Bars for Concrete Applications through Material Selection, Simulation, and Pathways for Future Development. *Journal of Sustainable Construction Materials and Technologies*, 2025, 10.3: 7.

[19] ZHAO, Hongbin, et al. Development, Challenges, and Applications of Concrete Coating Technology: Exploring Paths to Enhance Durability and Standardization. *Coatings*, 2025, 15.4: 409

Evaluation of the thermal comfort and indoor air quality in a military shelter under summer conditions

Evaluarea confortului termic și a calității aerului interior într-un adapost militar în condiții de vară

Manea-Andrei Damian¹, Ana-Andreea Vartires¹, Tiberiu Catalina¹,
Dragos Mihai¹

¹Technical University of Civil Engineering Bucharest, Faculty of Building Services and Equipment
B-dul Pache Protopopescu nr.66, sector 2, Bucharest, Romania

E-mail: andrei.damian@utcb.ro, andreea.vartires@utcb.ro, tiberiu.catalina@utcb.ro,
dragos.mihai@phd.utcb.ro

DOI: 10.37789/rjce.2026.17.3.18

Abstract. *The present paper presents a study of thermal comfort in a military tent, through numerical analysis using dynamic simulations, under summer climatic conditions. The topic was chosen based on the increasing importance of temporary structures in military activities, operational interventions, training camps or situations in which personnel must carry out activities in open field. The main goal was to evaluate thermal comfort in a military tent, by comparing several operational scenarios and by identifying solutions that can reduce overheating and improve the quality of the indoor environment. The results obtained are promising and should be confirmed by an experimental campaign.*

Key words: *thermal comfort, indoor air quality, military tents*

Rezumat. *Prezenta lucrare are ca obiectiv studiul confortului termic în corturi militare, prin analiza numerică a unui cort utilizat ca adăpost temporar pentru personalul militar, în condiții climatice de vară. Tema a fost aleasă pornind de la importanța structurilor temporare în activități militare, intervenții operative sau situații în care personalul trebuie să desfășoare activități în teren deschis. Scopul principal al lucrării a fost evaluarea confortului termic într-un cort militar, prin compararea mai multor scenarii de simulare și prin identificarea soluțiilor care pot reduce supraîncălzirea și pot îmbunătăți calitatea mediului interior. Rezultatele obținute sunt încurajatoare și vor trebui confirmate printr-o campanie experimentală.*

Cuvinte cheie: *confort termic, calitatea aerului interior, corturi militare*

1. Introduction

The study of thermal comfort in military tents and temporary shelters has become increasingly important in recent years due to the current geopolitical context marked by regional conflicts and humanitarian crises, facts that emphasize the need for more efficient temporary shelter solutions. Although these structures were created, in principle, for short-term use, in practice, they end up being used for long periods when returning to a permanent home is slow or impossible. Under these conditions, thermal comfort parameters and accumulated pollutant concentrations indoors no longer represent just a singular comfort issue, but one of health, safety and functionality of the occupied space.

Zheng et al. [1] selected and studied over 100 representative articles from a broad analysis of thermal comfort in temporary buildings, producing a synthesis that aims to organize the entire field of thermal comfort in temporary shelters. The article is not limited to a single type of shelter, but synthesizes the existing literature for temporary buildings, including tents, modular shelters, containers and other lightweight structures. The aim of the research was to find problems related to thermal comfort, assessment methods used in practice and improvement measures reported in different climatic zones. The users of these spaces are frequently dissatisfied with the quality of the indoor environment, and this problem occurs recurrently in most climatic zones. Thermal discomfort rates reach approximately 75% in hot and humid climates, 86.7% in hot and dry climates, 51% in temperate climates and 85% in cold climates. For example, in temperate climates, the authors showed that temperatures inside temporary buildings can vary between 7°C and 41°C throughout the year, with predicted mean vote (PMV) values outside the comfort range 60% of the time. These data show that temporary structures have very poor thermal performance and present difficulties in maintaining a comfortable indoor environment.

Crawford et al. [2] studied temporary shelters in cold climates by experimentally testing two shelter prototypes under controlled conditions, with the external temperature maintained at -20°C and compared the measurement results with numerical simulations in the ESP-r program. The aim of the research was twofold - on the one hand, to compare the performance of two constructive solutions (the total thermal conductance of one shelter was 54.29 W/K, and 63.82 W/K for the second prototype), and on the other hand, to develop well-calibrated evaluation tools that could be used to correctly simulate these structures under different conditions. An important result of the work was related to the thermal stratification of the air: both tents showed a significant variation in temperature with increasing height, the temperature difference between the lower and middle areas reaching up to 17°C. This shows that the average internal temperature is not an accurate parameter and can hide severe discomfort.

Cornaro et al. [3] analysed an emergency tent produced in collaboration with the Solar and Organic Energy Center. The authors studied the performance of a tent in both hot and cold climates, using an IDA Indoor Climate and Energy 4.5 dynamic simulation model calibrated using field data collected near Rome. The tent studied is

constructed of a steel structure, covered with a material composed of 50% cotton and 50% modacrylic synthetic fiber. Six photovoltaic panels with a power of 780 Wp were installed on the roof of the tent, which will produce between 300Wh/day and 4 kWh/day depending on the season. Cornaro's study [3] shows the levels of poor performance of a tent in winter and how much these effects can be improved by using thermal insulation of the tent envelope structure. In addition, in hot climates, the study proves that in addition to using insulation, reflective shading elements are needed to reduce daily solar gains.

Y. Jiang [4] directly assessed the thermal comfort of soldiers in military tents during summer. The study was conducted in Tianjin, for four outdoor military tents, with 30 investigations being carried out between 8 am and 6 pm to study the effects of the indoor environment on soldiers during the hot period. The study consisted of questionnaires being completed by groups of 10 people, with almost 100 soldiers being interviewed for this experiment. Also, in addition to the questionnaires completed by the soldiers, the author measured indoor parameters such as temperature, relative humidity and air velocity to correlate the physical parameters with the direct perception of people. Jiang defined a scale with values ranging from -3 (very cold feeling) to +3 (very hot feeling), with the value 0 being for the thermal neutral zone. The indoor air temperature ranged between 22.06°C and 33.4°C, while the outside temperature ranged between 22.8°C and 26°C, so the temperatures inside the tent were higher than those outside; the average relative humidity was 61.97%. The study shows that the vote for thermal sensation 0, i.e. neutral, was for the range 26-28°C.

At the same time, Liu et al. [5] studied a simple passive solution to increase thermal comfort by installing textile shade nets over a military tent. For this experiment, two shade nets were compared, one with a shade rate of 75% and the other with a shade rate of 96%, both mounted one meter above the tent. The test took place in Tianjin city, on a day when the outside temperature varied between 20°C and 28°C. To conduct the experiment, the authors used 25 thermometers placed at five different heights: 0.1m, 0.5m, 1m, 1.5m, 2m. In addition, the authors measured the relative humidity both inside and outside and monitored the temperature on the inner surfaces of the envelope. The study's conclusions show that the 96% shading net should be preferred, as it reduces solar gain much better and thermal stratification is less pronounced. The authors propose extending the shading surface to the tent walls, as well as optimizing the position and size of the windows.

Tan and Tan [6] compared the performance of a tent with that of a standard temporary shelter configuration (container type) under subtropical summer conditions in Taiwan, using both experimental measurements and computational analysis. During the time interval 9:30-14:30 in the center of the tent, the air temperatures at heights of 0.1m, 1.1m, 1.7m were 3.1°C, 5.5°C and 6°C higher than the outdoor temperature. In contrast, in the standard shelter configuration, the temperatures measured at the same points were 1.2°C, 0.5°C and 0.7°C lower than the same outdoor temperature. In other words, the tent enhanced the heating of the indoor air, while the standard shelter configuration was able to maintain temperatures below the outdoor temperature. In terms of PMV and PPD (Predicted Percentage of Dissatisfied) indices, the standard

configuration recorded an average PMV of 3.14 and PPD of 100%, while the tent had a PMV of 5.03 and the same PPD of 100%. Neither was the shelter able to maintain a comfortable indoor environment, but the level of heat stress was significantly more severe in the tent.

The PhD thesis of R. Poschl [7] is one of the most consistent works in literature on thermal comfort in humanitarian tents. The study included field monitoring for six months, dynamic thermal modelling and CFD modelling. The author used a real standardized tent, installed in the UK, then calibrated numerical models that were subsequently applied for cold, temperate and warm climates. For the cold climate, one of the most important conclusions is that changing the material for the walls and roof increases the difference between the indoor and outdoor temperature from 30 K to 39 K, i.e. by 9 K. In addition, the number of hours of thermal comfort according to the PMV-PPD index criteria increased from 10.50 hours to 23.00 hours. This is a very large increase and shows that improving the envelope material has a direct effect on the real possibility of achieving a thermal state closer to optimal comfort. Interestingly, the number of hours in which a state of good thermal comfort is observed assessed only by the indoor air temperature decreased from 17.25 to 16.00 hours, which shows that assessing comfort based only on air temperature is incorrect and that changing the material also changes other comfort parameters.

For hot climates, Poschl [7] shows that simply increasing the ventilation openings does not solve the problem. In the best-case scenario of increased opening, the PMV range improved from +1.7...+3 to +1.5...+3, i.e. by only 0.2 units. The maximum PPD value decreased from 72.4% to 62.4%, i.e. by 10 percentage points, and the interior temperature in the hottest part of the day decreased from 75.2°C to 72.5°C. In other words, the additional ventilation helps a little, but the thermal comfort in the tent does not improve significantly.

In contrast, changing the shading strategy and increasing the reflectance of the envelope material had much greater effects. The author shows that the PMV index improved from 2.9 to 2.6, and the maximum PPD value decreased from 95.7% to 91.2%. The most important finding is the reduction of the indoor air temperature by 23 K compared to the basic tent. Even so, the results summarized by the author show that even the optimized variant does not provide acceptable hours according to the PMV/PPD criteria in very hot climates: both the basic tent and the “large opening” and “modified shading” variants have 0 hours of comfortable environment.

The important conclusion of the thesis is that some solutions clearly work better than others, but in very severe climates even good solutions are not enough to transform the tent into a thermally comfortable space. In cold climates, improving the envelope can double the acceptable hours after PMV/PPD, and in warm climates the use of reflective materials can lower the interior temperature. However, in extreme climates additional measures are also needed – for example, additional blankets and clothing for the cold or active cooling solutions in very hot environments.

Lee et al. [8] reached the same conclusion, showing that advanced materials used for tent envelope insulation and shading can bring modest improvements to the

thermal comfort during the warm season, and correct infiltration modelling can have a greater impact on thermal comfort in the cold season.

The study conducted in this paper aims to evaluate the thermal behaviour and indoor air quality for a small, lightweight military tent-type structure, typical of the Romanian Army, through numerical simulations performed for a standard (reference) tent, as well as for an identical tent for which different scenarios for improving the indoor environment in Bucharest summer conditions were applied. It follows the main hypothesis carried out in the paper entitled: “Analysis of possible overheating countermeasures applied to a Romanian military tent by means of numerical simulations”, which was accepted for the presentation at the RoomVent 2026 Conference, to be held in Prague, between 15th and 18th September 2026 [9]. The present paper will focus on the influence of improved ventilation scenarios related to those presented in [9], as well as on the indoor air quality (IAQ) obtained indoors by using these scenarios.

2. Description of the investigation method and case studies

The analysis of the thermal comfort presented in this paper relies on the PMV-PPD Fanger theory, certified by the European standard EN 7730 [10]. Therefore, we performed dynamic simulations with the Design Builder simulation software, during a one-week summer period (1st-7th July, corresponding to the weather file for Bucharest, Romania, available within the Design Builder weather database), to assess the variation of the thermal comfort index PMV within a temporary military shelter, while assuming two methods to counteract excessive overheating: shading and mechanical ventilation with outdoor air.

The Design Builder simulation program (educational license) was used to perform numerical simulations of shading and ventilation scenarios for a military shelter located in the city of Bucharest, Romania. This program was conceived to analyse thermal building behaviour, energy performance of the systems linked to buildings (heating, ventilation, air-conditioning) through dynamic simulations, which allows also the assessment of thermal comfort and the verification of the influence of different comfort improvement solutions on the indoor environment, using dynamic calculations based on the Energy Plus simulation engine.

To model the military tent thermal regime, the most important categories of input data entered into Design Builder interface are the building envelope (walls, windows, slabs), the schedules for daily human occupancy, for occupant's activities, properties of opaque and transparent materials, lighting systems, HVAC systems and their operating schedules. Each of these categories influences the results of the simulation, either through internal heat gains, heat transfer through the envelope, or air exchange between the outdoor and indoor environment.

The analysed tent is a real one, in terms of shape, materials and dimensions, typically used by the Romanian army within latest decades, with plan dimensions of 3.60×3.60 m and a two-slopes pitched roof (Fig. 1). The height of the side walls is

1.60 m, and the maximum height in the ridge area is 2.30 m. The tent has a surface area of 12.96 m² and a volume of 25.27 m³.

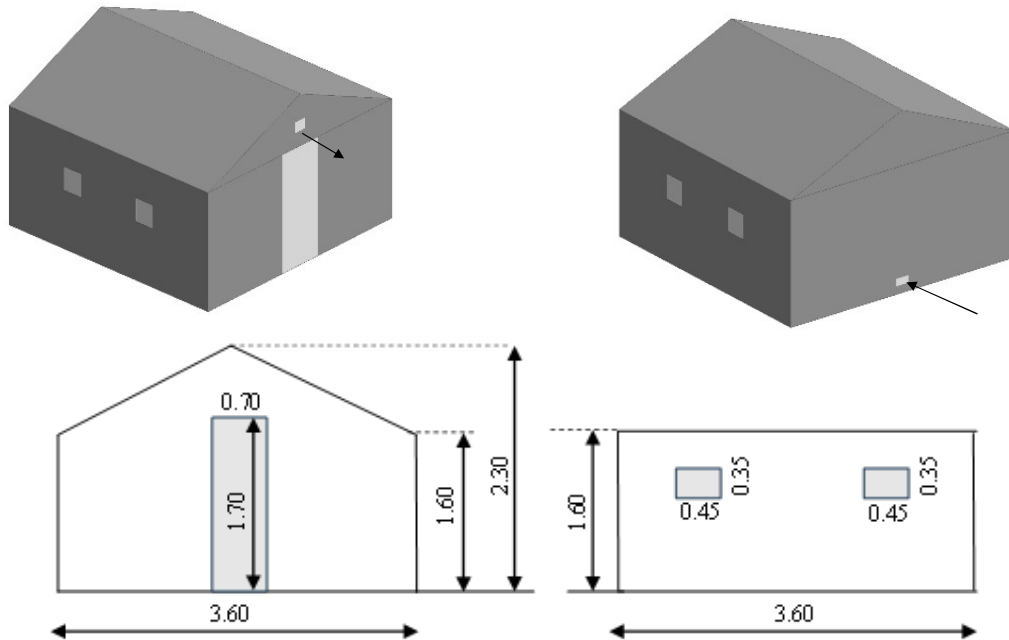


Fig. 1. Sketch-up of the simulated tent and its geometric dimensions (m) [9]

The material of the tent envelope is textile fabric, and its behaviour is not only influenced by the thermal conductivity of the material, but also by the way in which the material reflects or absorbs solar radiation. The textile fabric has a thermal conductivity of 0.04 W/m·K and a solar radiation absorption coefficient of 0.90. The tent envelope contains 4 windows (made of plexiglass) mounted on opposite facades, with a thickness of 3mm and a thermal conductivity of 0.19 W/m·K. In terms of optical properties, the plexiglass was defined as a solar transmittance of 0.90, and the external and internal solar reflectance was 0.08. These values show that the material allows a very large proportion of the incident solar radiation to pass through to the interior, while only a small part is reflected by the external or internal surface.

The internal heat gains were considered as follows: for lighting 5 LED bulbs, each with a power of 5 Wp, resulting in a total installed power of 25 Wp (operating only in the evening, between 19:00 and 22:00) and a maximum occupancy of 8 people. During the day, the heat gain from people inside was 125 W/person (light physical activity), respectively 70 W/person during nighttime, due to the reduced activity inside the tent (sleeping). During a day, training, rest and administrative activities are considered (Table 1). The total installed power for lighting being low in relation to the occupants' emissions and the effects of solar radiation on the envelope, the lighting did not have a visible influence on the internal environment but was included to more accurately represent the way the tent is used.

Table 1

Daily occupation schedule for the analysed tent [9]			
Period of the day	Type of activity	Number of people present in the tent	Metabolic heat emitted (W/person) [10]
6:00 – 7:00	Wake-up time	Eight	125 (light physical activity)
7:00 – 8:00	Breakfast time	No people	0
8:00 – 12:30	Training activities	No people	0
12:30 – 13:30	Lunch time	No people	0
13:30 – 19:00	Mixed activities	Four	125 (light physical activity)
19:00 – 20:00	Dinner time	No people	0
20:00 – 21:00	Administrative activities	Six	125 (light physical activity)
21:00 – 6:00	Rest during nighttime (sleeping)	Eight	70 (low activity, sleep)

In table 2 are presented the three improved mechanical ventilation scenarios imagined for the simulations of thermal comfort and indoor air quality, as related to [9]. In fact, the V2 scenario remains the same as the similar V2 presented in [9], while the V3 scenario suppose a double airflow rate reported to V2 (200 m³/h), more appropriate to remove the excess heat from the tent during the high solar gains period (daytime). The scenario V1 is similar with the correspondent V3 from [9], with the single difference in the airflow rate during periods of human absence, which is doubled (50 m³/h- 2 ach, instead of 25 m³/h-1 ach) also for reasons of a better excess heat removal. Concerning the airflow rates corresponding to the period of human presence, they are calculated according to the equation (2), given by the Romanian norm for design, execution and commissioning of the ventilation and air-conditioning installations, IS-2022, for non-residential buildings [11]:

$$q_{fa} = N_p * q_A + A_o * q_B \quad (1)$$

where:

q_{fa} - the fresh airflow rate for ventilation purposes, supplied from outdoor (m³/h),

N_p – number of people present indoors (0 to 8), variable upon the schedule (Table 1),

q_A – specific airflow rate depending on the ambience category (m³/h*person),

A_o – occupied area (m²), equal to 14 m²,

q_B – specific airflow rate depending on the ambience category as well as on the potential pollution issued by the building itself (m³/h*m²).

Table 2

Ventilation scenarios proposed for the simulations

Ventilation scenario number	Airflow rate	Schedule
Ventilation scenario No.1 (V1)	Variable according to the schedule and calculated with equation (2)	25 m ³ /h – during nighttime 50 m ³ /h – during absence 120 m ³ /h – 4 people present 170 m ³ /h – 6 people present 220 m ³ /h – 8 people present (excepting nighttime)
Ventilation scenario No.2 (V2)	100 m ³ /h (4 ach), or 25 m ³ /h (1 ach)	100 m ³ /h (4 ach) during daytime (7:00-21:00), 25 m ³ /h (1 ach) during nighttime (21:00-7:00)
Ventilation scenario No.3 (V3)	200 m ³ /h (8 ach), or 25 m ³ /h (1 ach)	200 m ³ /h (8 ach) during daytime (7:00-21:00), 25 m ³ /h (1 ach) during nighttime (21:00-7:00)

Concerning the shading measures to be taken, we proposed the same two solutions for the tent pitched roof covering, as in [9], outlined in table 3.

Table 3

Shading solutions proposed and characteristics [9]

Thermal and optical characteristics	Shading solution No.1 (U1) (Aluminium foil)	Shading solution No.2 (U2) (Shade net)
Thermal conductivity (W/m*K)	237	0.5
Specific heat mass (J/kg*K)	900	930
Mass density (kg/m ³)	2700	1300
Thermal absorptance (-)	0.05	0.4
Solar absorptance (-)	0.1	0.4
Visible absorptance (-)	0.1	0.4
Transmissivity (-)	0.0	0.4
Reflectance (-)	0.9	0.2

3. Results and discussion

In figures 2 and 3 we present the 7-days (equivalent to 168 hours) variation of indoor operative temperatures and PMV indexes obtained by numerical simulations, for the three shading situations assumed (no shading, shading U1 and shading U2), along with the variation of the outdoor temperature. The ventilation scenario applied for this simulation was V1, according to Table 2. We could notice from these figures that, during the warmest day periods, corresponding to the superposed effect between outdoor temperature and solar radiation (11:00 to 17:00), the indoor operative

temperatures exceed 35 °C (excepting day 7, the coldest of the week), while PMV-s exceed the value of +3 (hot, according to the Fanger comfort scale [10]), for the same time intervals. Moreover, it appears clearly that the "no shading case" is the worst related to thermal comfort, while the shading case U1 (Aluminium foil) seems to be the most favourable one. As expected, the shading case U2 (shade net with 40% solar transmittance) lies between these two extreme cases. This behaviour could be explained by the high reflectance (0.9) of incident solar radiation that characterises the Aluminium foil. Meanwhile, for the shade net solution, the reduced transmittivity of light lowers the temperature increase of the tent roof material compared with the "no shading case", but with a lower efficiency of heat transmission indoors compared with the Aluminium foil case.

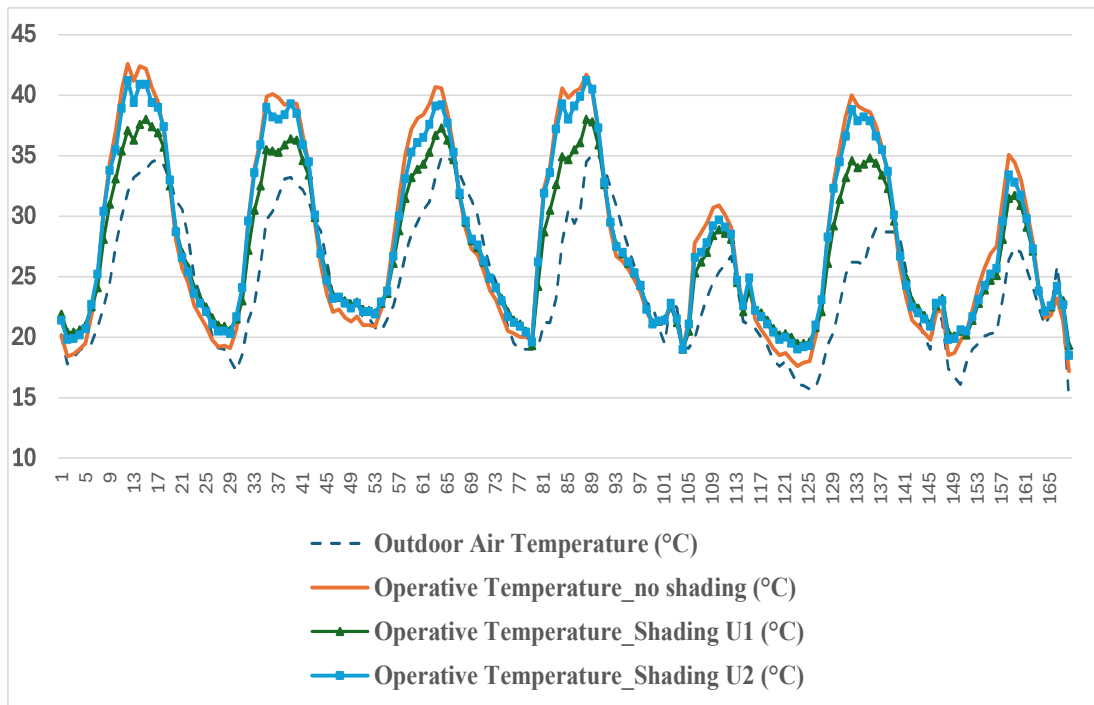


Fig. 2. Comparison between indoor operative temperatures obtained by applying the ventilation scenario V1 for the two types of shading (U1 and U2) and the "no shading".

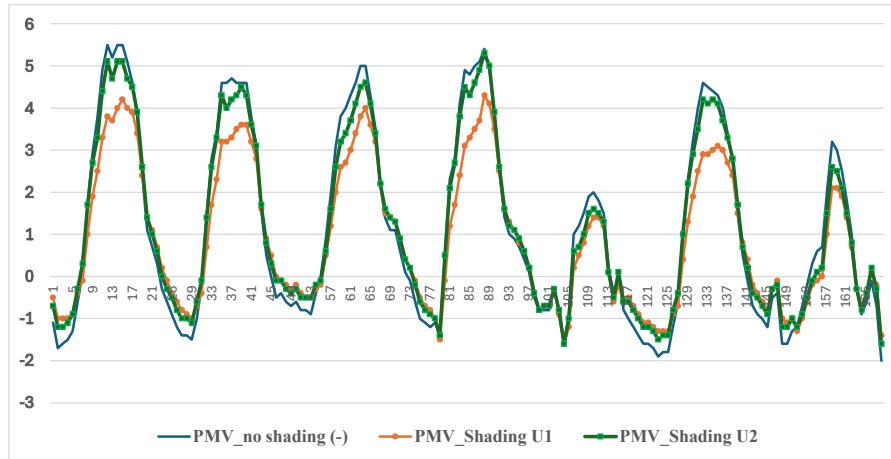


Fig. 3. Comparison between indoor global PMV's (Predicted Mean Votes) by applying the ventilation scenario V1 for the two types of shading (U1 and U2) and the "no shading case".

In fig 4. is presented the comparison between indoor operative temperatures obtained by applying the best ventilation scenario, V3 (8 air changes per hour during daytime and 1 ach during nighttime) for the two types of shading (U1 and U2) and the "no shading case", while in fig.5 is outlined the similar variation of the PMV-s obtained under the same hypothesis.

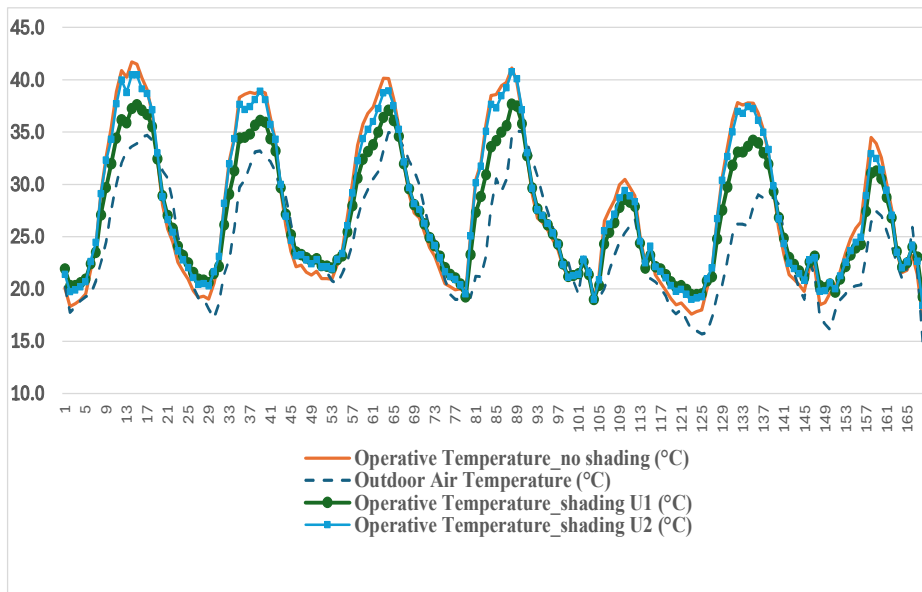


Fig. 4. Comparison between indoor global PMV's (Predicted Mean Votes) by applying the ventilation scenario V3 for the two types of shading (U1 and U2) and the "no shading case".

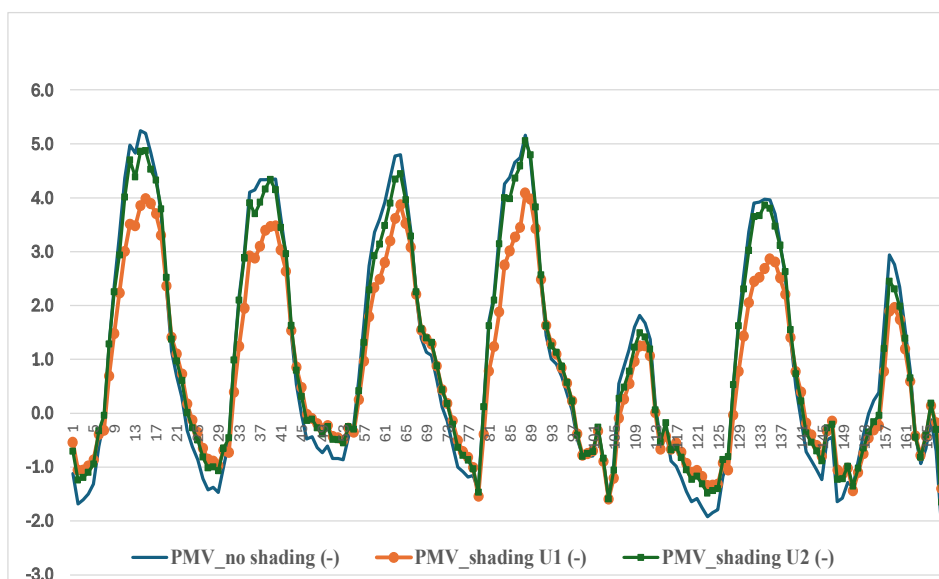


Fig. 5. Comparison between indoor global PMV's (Predicted Mean Votes) by applying the ventilation scenario V3 for the two types of shading (U1 and U2) and the "no shading case".

The conclusions emerging from these two graphs are similar to those explained for the ventilation scenario V1, with the single difference in the lowest peaks of operative temperatures and PMV-s, which is due to the highest airflow ventilation rate (Table 2), which is supposed to evacuate more excess heat from the analysed tent.

In the figures 6 and 7 are represented the variations of the operative temperatures and PMV-s, assuming the same shading case (U2 in fig.6 and U1 in fig.7), but three different mechanical ventilation scenarios (V1, V2 and V3). We could observe from each of these graphs that the scenario V3 (green line) is the best (lowest peaks of operative temperatures and PMV-s), while the scenario V2 (constant airflow rate of 100 m³/h during daytime) appears to be the be slightly worse than V1, but very close to it. However, the differences between the peaks obtained by the simulation of these scenarios are quite low, keeping thus in mind that the influence of the ventilation rate with outdoor air doesn't bring a substantial improvement on the thermal comfort, in the absence of any active or passive cooling method.

However, when comparing fig.6 to fig.7, we could notice that the peaks of operative temperatures and PMV-s for the shading case U1 are sensibly lower than those obtained for the shading case U2. Therefore, it is obvious that the efficiency of the shading method has much more influence on the thermal comfort than the ventilation airflow rate during the daytime, when the thermal load is heavy (temperature and solar radiation).

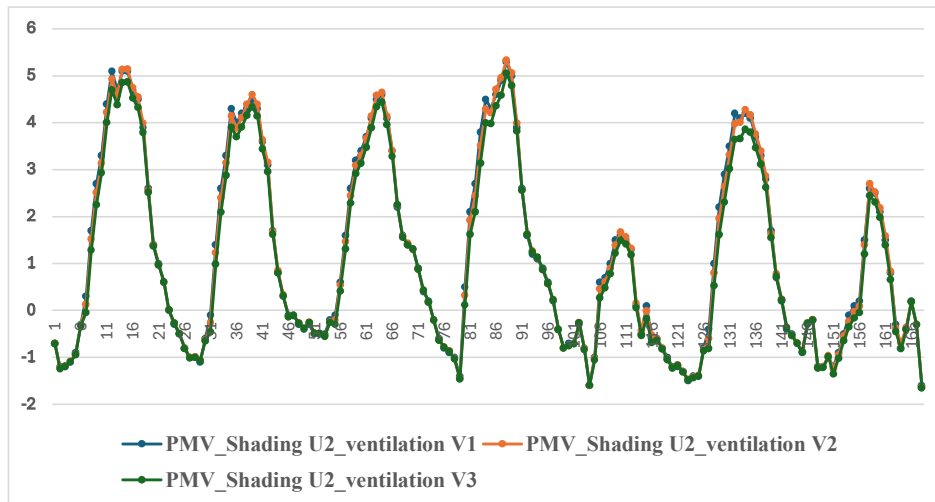


Fig. 6. Comparison between indoor global PMV's (Predicted Mean Votes) by applying the three ventilation scenarios (V1, V2 and V3) for the shading case U2

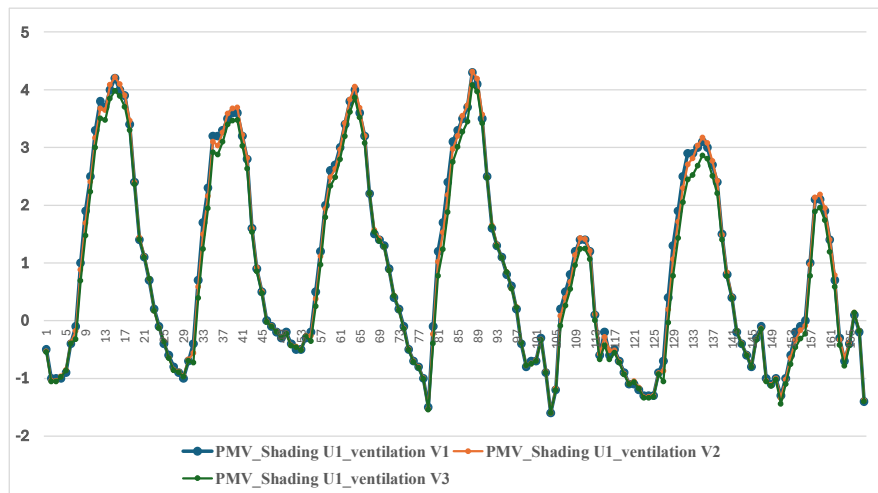


Fig. 7. Comparison between indoor global PMV's (Predicted Mean Votes) by applying the three ventilation scenarios (V1, V2 and V3) for the shading case U1

Concerning the influence of the ventilation scenarios on the indoor air quality (IAQ) related to CO₂ indoor concentrations (in ppm unit), we represented in fig.8 a comparison between the V1, V2 and V3 scenarios, for the shading case U2, for the whole 7-days simulation period. We can notice from this figure that the best scenario for IAQ is V3 (with the highest airflow rate), where the maximum CO₂ indoor concentration (green line) reaches approximately 900 ppm, when for the other two scenarios (V1 and V2), the concentrations are very close and the peaks are slightly surpassing the threshold limit of 1000 ppm, at the hour with maximum occupancy. During nighttime we could notice that indoor CO₂ concentrations decrease at 400-500 ppm values (very good IAQ), which could be explained by very low CO₂ emissions through respiration, by the sleeping occupants, as well as by the outside CO₂

concentration, equal to 350 ppm. A similar concentrations behaviour was observed for the shading case U1.

Therefore, we could assess that all the ventilation scenarios imagined are satisfying the IAQ condition related to CO₂ concentration, regardless of the shading solutions adopted.

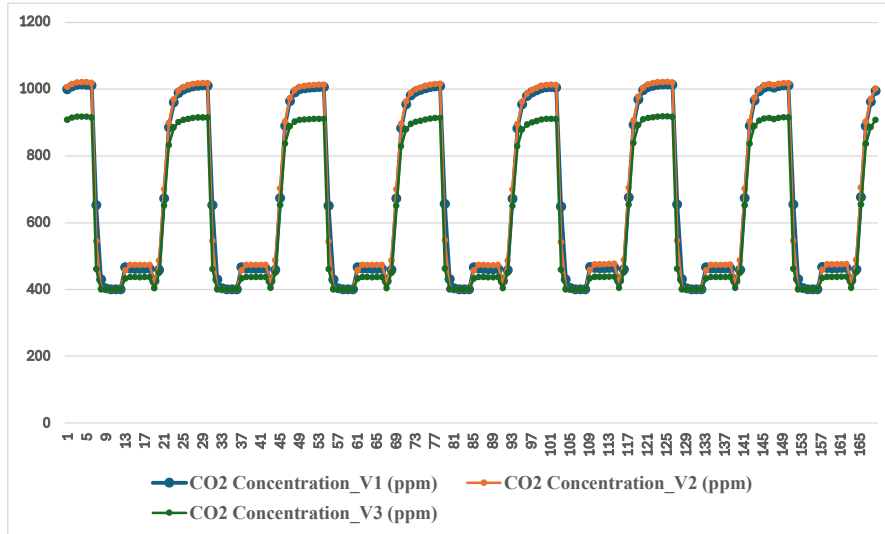


Fig. 8. Comparison between indoor CO₂ concentrations by applying the three ventilation scenarios (V1, V2 and V3) for the shading case U2

4. Conclusions

The main conclusions that could be highlighted from this numerical study are:

- The efficiency of the shading method is crucial in regard with the indoor thermal comfort, but could not alone reduce the PMV values below "+3" (sensation of Hot environment) during daytime (highest cooling loads), in the absence of any passive or active cooling system;
- The mechanical ventilation plays an important role in maintaining CO₂ concentrations indoors below the threshold value of 1000 ppm, considered as the maximum limit of the "fresh air state"; however, any ventilation scenario chosen, even with the highest airflow rates (8 air changes per hour during daytime) could not assure indoor thermal comfort when outdoor temperatures reach peak values as high as 35 °C or bigger;
- Even that the ventilation scenarios could not ensure the thermal comfort sensation during daytime, the increase of outdoor airflow rate leads to the decrease of indoor operative temperatures peaks, as well as of PMV-s peaks;
- During nighttime, the situation changes, in the sense that the thermal comfort improves considerably after 8:00 PM, while after 2:00 AM and 6:00 AM the calculated PMV-s could reach even "-2" values (sensation of

Coldness), knowing that the occupants are wearing light clothes (0.5 clo thermal resistance, equivalent to summer period) and their internal metabolism is very low (sleeping period); this rapid change in thermal sensation during the day cycle could be explained obviously by the very low thermal inertia of the tent structure.

The research presented in this paper will be completed with results issued from an experimental campaign performed during the summer 2026 (July-August 2026), corresponding to an identical tent with the one described in Figure 1, and considering similar scenarios of mechanical ventilation and shading.

Acknowledgement

This work was supported by a National Research Grants of the UTCB, project number GnaC ARUST 2025-UTCB 19.

References

- [1] *P. Zheng, H. Wu, Y. Liu, Y. Ding, L. Yang*, Thermal comfort in temporary buildings: A review, Building and Environment, 2022.
- [2] *C. Crawford, P. Manfield, A. McRobie*, Assessing the thermal performance of an emergency shelter system, Energy and Buildings, 2005.
- [3] *C. Cornaro, D. Saporio, F. Bucci, M. Pierro, C. Giammanco*, Thermal performance analysis of an emergency shelter using dynamic building simulation, Energy and Buildings, 2015.
- [4] *Y. Jiang*, Investigation and research on thermal comfort of soldiers in military tent in summer, Journal of Physics: Conference Series, 2019.
- [5] *J. Liu, Y. Jiang, Z. Gong, H. Yang*, Experiment Research on Shading to Improve the Thermal Environment of Tents, MATEC Web of Conferences, 2016.
- [6] *A. Y. Kwang Tan, C. Keong Tan*, Thermal Comfort Performances of Temporary Shelters Using Experimental and Computational Assessments, Buildings, 2021.
- [7] *R. Pöschl*, Modelling the Thermal Comfort Performance of Tents used in Humanitarian Relief, PhD Thesis, Loughborough University, 2016.
- [8] *D.S. Lee, M. Iacocca, Y.K. Joshi*, Energy usage modeling for heating and cooling off-grid shelters, Journal of Building Engineering, 2021.
- [9] *M.A. Damian, A. Vartires, T. Catalina, M. Dragos*, Analysis of possible overheating countermeasures applied to a Romanian military tent by means of numerical simulations, accepted for publication at the RoomVent 2026 Conference, Prague, 15-18 September 2026.
- [10] EN ISO 7730:2006: Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria
- [11] Romanian norm for the design, execution and commissioning of the ventilation and air-conditioning installations, IS-2022 (Online)