IOSUD - Universitatea Politehnica Timişoara
Şcoala Doctorală de Studii Inginereşti

THE SUSTAINABILITY OF AN INSULATION SYSTEM WITH PARALLEL AIR LAYERS FOR ENERGY EFFICIENT BUILDINGS - THEORETICAL AND EXPERIMENTAL STUDIES

PhD Thesis – Summary

To obtain the scientific title of Doctor at

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In the field of Civil Enginering and Building Services

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Abstract

In case of buildings, efficiency is evaluated not only upon generated emissions during the operation phase, but also according to the embodied emissions of the building materials and relating technical equipment's. As a consequence, in addition to the techniques of generating and providing sustainable energy the implementation of highly efficient building materials has become crucial.

Because the operational energy of highly efficient buildings has been reduced, the relative impact of embodied energy has increased and its importance must be recognized.

This thesis contains preliminary studies regarding the sustainability of an innovative insulation system based on existing insulation materials enhanced with insulating air chambers. Firstly, the thermal properties of the innovative system are tested under laboratory conditions in comparison to an existing insulation system used at one of the first public building built in Romania according to passive house standards.

Then after, the efficiency of the system is assessed and compared with the existing insulation system of the building. The comparisons are made using both theoretically estimated energy consumptions and the real ones measured during the exploitation of the building. For both insulating systems, the emissions generated during production and maintenance stages were assessed based on the theoretical calculation and according to the thermal conductivity of the insulation systems obtained during the laboratory tests.

Furthermore, the behaviour of the system is investigated according to different national climate zones.

Summary of thesis chapters

1. Introduction

1.1 <u>General aspects of energy efficiency and sustainability</u>

The consumption of resources and emissions of harmful gases is expanding beyond the absorption capacity of the environment. The global buildings sector is growing at remarkable rates [1].

1.2 <u>Policy actions</u>

Fortunately, several opportunities can be taken up in order to achieve energy-efficient and low-carbon solutions for the construction sector.

1.3 European Union perspective to climate change

To cope with the global energy challenge and the consequences of climate change, energy efficiency improvements the European Union adopted the 2020 Climate and Energy Package in March 2007. The EU framework contains several proposals, also known as the '20-20-20' targets related to the energy efficiency and the reduction of generated harmful gases.

1.4 Energy use in the building sector

To achieve the reduction of the emissions assumed at European level the member countries have to implement national measures to increase the efficiency of the building stock.

1.5 Main features of energy consumption according to the building sector in Romania

To reduce energy intensity in the major energy-consuming sector and attain the proposed targets [2], the most important measures regarding the building sector is:

- Rehabilitation of the thermal envelope of the building;
- Increasing the efficiency of building systems.

In this idea, the calculation methodologies [3] [4] [5], are becoming increasingly rigorous regarding the efficiency of the rehabilitations and new constructions.

1.6 Research motivation and objectives

The primary challenge in achieving the targets established by the Energy Performance of buildings Directive lies in providing highly energy efficient solutions that at the simultaneously have a sustainable number of embodied emissions.

In an attempt to reduce the emissions contained in the insulation system and thus in the entire building, while preserving the energy efficiency, the work aims to study the sustainability of an innovative insulation system. The innovative system is based on existing rockwool panels, but contains multiple additional air layers. The purpose of the air layer is to ensure increased insulation properties of the envelope system but with the same amount of embedded energy.

The research aims to clarify the following:

- To investigate the most effective structure of the innovative insulation system;
- To investigate the optimal air layer thickness;
- T investigate the influence of the air layers on the thermal conductivity;
- To determine the influence of the new system on the energy consumption and on the emission generated by the case study building.

1.7 Overview of the thesis

The thesis is structured in six chapters and six appendixes. The content of the six chapters and one Appendix has a total number of 204 pages.

2. Certification tools and certification concepts of highly efficient energy buildings

This chapter presents various energy efficient building concepts that have gained popularity in recent years at European and global level.

2.1 Certification tools

2.1.1 Leadership in Energy and Environmental Design (LEED)

The subchapter presents the basic characteristics of the LEED standard.

2.1.1 Building research establishment environmental assessment method (BREEAM)

The subchapter presents the basic characteristics of the BREEAM standard.

2.2 Energy efficient building concepts

2.2.1 Nearly zero energy building (NZEB)

The subchapter presents the basic characteristics of the NZEB standard. The adaptation of the standard regarding the requirements to produce the energy demand at < 30 km from the building site are also presented.

2.2.2 Passive house (PH)

The subchapter presents the basic characteristics of the passive house standard.

2.2.3 Passive house schools (PH)

The subchapter presents the basic characteristics of the passive house schools.

3. Case study building

The present research is based on a high school building, one of the first public buildings constructed in Romania according to the Passive House prescriptions. The building is located in the city of Salonta.

3.1 Thermal properties of the building's envelope

The thermal properties of the existing envelope system are presented how they were provided by the designing team [6].

3.2 Building structure

The structure of the high school building, the interior finishings and the architecture of the case study building are presented as they were provided by the designing team [6].

3.3 Building systems

The building systems of the case study building are presented as they were provided by the designing team [6].

3.3.1 Permeability of the case study building

For high efficiency new buildings, air tightness measurement is mandatory. The air tightness was checked at the end of the construction work by the design team together with an extended research team from the Politehnica University of Timisoara. The verification was conducted using a blower door test. Based on the first results, air infiltrations were reduced by multiple adjustments of the areas exposed to air where tightness leaks were identified. Following the interventions, the building met the requirements regarding the maximum number of air exchanges imposed by the passive house standard.

3.3.2 Monitoring system of the high school building

This chapter presents a complex monitoring system used in the reference building, composed of temperature, humidity, CO2 sensors, and utility metres. The system allows both real-time monitoring of the performance and optimization of the energy consumption in various construction sectors with different destinations.

3.3.2 Monitoring data processing

The following section contains the figures according to the measured energy consumptions of the high school building during the first 21 months of operation. Due to incomplete utilization of the building, the chapter contains also the estimated increase of the monitored data according to the estimates of the designing team.

3.3.4 General Considerations

Because the used models are not able to cover all real influences of the building, the assumptions and limitations considered during the study are presented in this chapter.

3.4 Initial to operating cost analysis according to design team calculations

The preliminary cost analysis of the designing team states that, the cost difference between a regular insulated building and a solution at PH standards should be absorbed in no more than 6 years by the reduced maintenance costs [6].

3.5 Hygrothermal simulations

In order to fully understand the comfort and energy consumption of buildings, the simulation of the hygrothermal response aside the insulation properties were assessed using the software for higrodinamic calculation WUFI [7]. This performs the hygrothermal calculations taking into account the dynamic simulations of coupled heat and moisture transfer.

3.5.1 Geometric model

The basis of the hygrothermal simulation consists of the geometric building model, in which the location, dimension and all the related building components are defined. The building was simulated using the building wizard provided by the hygrothermal calculation software WUFI [7].

3.5.2 Parametrii numerici și datele de intrare ale simulării

This chapter includes the parameters of the building but also of the surroundings. All the data presented were taken into account in the simulation of the general hygrothermal behaviour of the building.

3.5.3 Dependence of the heat conductivity on moisture

The dependence of the heat conductivity on the moisture content of the materials was presented and taken into account by linear interpolation according to the material moisture content.

3.5.4 The diffusion resistance factor (μ-value)

The calculation of the diffusion resistance factor, i.e. the parameter that determines the exchange of moisture between the building materials and the surrounding environment is presented in the following section. The calculations are carried both for existing insulation system but also for the ISPA.

3.5.5 Vapor diffusion thickness, (sd-value)

The calculation algorithm used by the software in order to simulate the diffusion thickness of the building materials is presented in the following section.

3.5.6 Permeance

The permeance, i.e. the rate of water vapour over the course of one hour through one square foot of a material of a given thickness at a specified vapour pressure, is presented in the following section.

4. Insulation system with parallel air chambers (ISPA)

The growing requirements regarding minimum insulation properties also imply additional concerns about embodied energy and harmful emissions generated during the building material manufacturing process [8]. In Romania, the methodology regarding energy efficiency in the building industry (3) (4) (5) imposes increasing demands of the envelope insulation properties. The minimum required performance of the thermal envelope is increased with 68.75% for outer walls and 42.0% for the upper slab.

4.1 Literature review

In the current section there are presented the numerous previously available literature that is focused on the thermal performance of unventilated air layers in building envelopes. The are based on the well-known theoretical knowledge to which there are four types of heat transfer patterns in unventilated air layers (pure conduction, radiation, laminar, and turbulent convection). Furthermore, the convective pattern is bounded by two dividing points. The first divides pure conductive flux from convective flux, and the second divides the laminar regime from turbulent regime.

4.2 Heat transfer mechanisms

4.2.1 Convection

The subchapter presents the heat transfer phenomenon through convection, its properties and the calculation model.

4.2.2 Conduction

The subchapter presents the heat transfer phenomenon through conduction, its properties and the calculation model.

4.2.3 Heat radiation

The subchapter presents the heat transfer phenomenon through radiation, its properties and the calculation model.

4.3 Grosimea inițială a straturilor de aer

The preliminary calculation of the air layer thickness was performed using the stationary thermophysical calculation software – Antherm [13]. The chapter contains the principles which support the design of the insulating panel.

The novelty of the proposed insulation system (ISPA) lies in the transfer of an idea used for structural strength elements - castellated beams to thermal insulation systems. The lay-out of air layers within the insulation panel is shown in Figure 1:

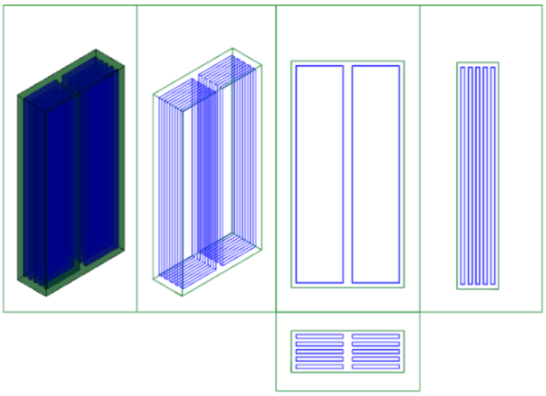


Figure 1. The lay-out of air layers within the insulation panel.

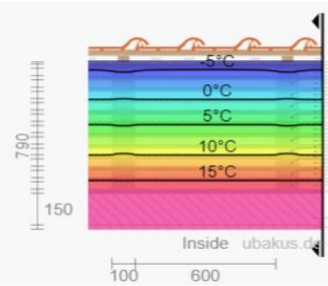
4.4 Preliminary investigations conducted on insulation systems with parallel air chambers

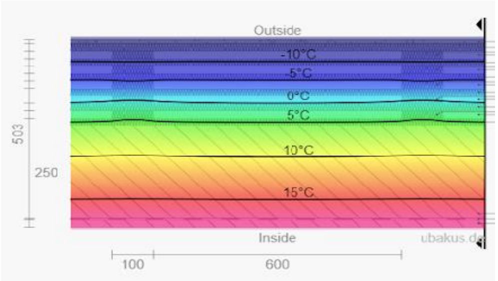
4.4.1 Laboratory investigations

The following section shows the average thermal conductivity of the insulating as measured during laboratory tests. The mean thermal conductivity determined with the measuring device, λ-Meter EP500e [9], and determined to 0.03907 W/(m·K) for the existing insulation panel (solid rockwool) and 0.04196 W/(m·K), with 6.9% higher for the probes according to ISPA.

4.4.2 Temperature gradient inside the cross section of the envelope elements

The temperature variation throughout the envelope layers was determined by the author and replicated with the help of another steady-state calculation software – Antherm [13]. These were carried out in order to confirm the thermodynamical Equations used in the previous chapters. The temperature variation (isotherms) through the cross-section elements of the envelope is presented in Figure 2:





(a) (b)

Figure 2. (a) Upper slab (b) Exterior wall

4.4.3 Vapour permeability of the insulation system

The influence of the additional air layers on the water content of the insulation materials has been computationally determined using a dedicated software, WUFI [7].

4.4.4 The effective water vapor diffusion resistance factor

The actual thermal resistance of the air layer was replicated by selecting an effective heat conductivity.

4.4.5 Moisture storage function of the air layer

The moisture behaviour of the building materials was computationally assessed using a dedicated software, WUFI [7].

4.4.6 Capillary moisture region

At higher relative humidities, the sorption isotherm increases dramatically. The capillary moisture regions were computationally assessed using the dedicated software WUFI [7].

4.4.7 Supersaturated region

The moisture behaviour of the building materials was computationally assessed using a dedicated software, WUFI [7].

4.4.8 Approximation of the moisture storage function

The approximation of the moisture storage function computationally assessed using a dedicated software, WUFI [7].

4.4.9 Liquid transport mechanism

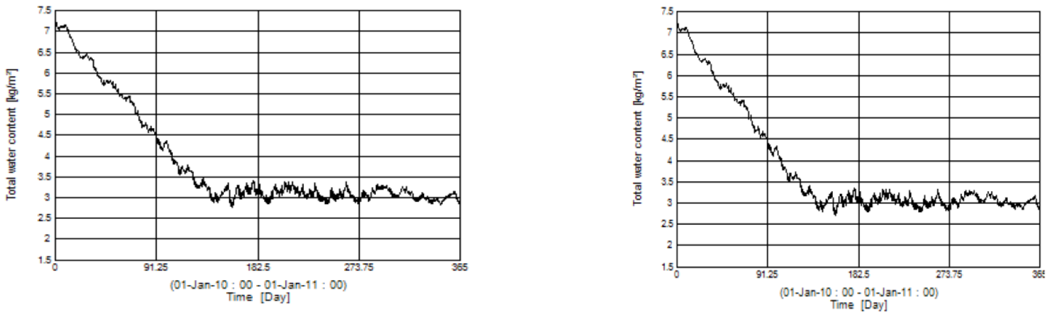
The interaction between water diffusion and liquid transport in building components was computationally assessed using a dedicated software, WUFI [7].

4.4.10 Membranes

The consideration of the membranes was selected as to replicate as good as possible the actual effect in the computational simulation. The information underlying the calculation algorithm are presented in this chapter. The calculations were conducted with the software WUFI [7].

4.4.11 Simulation of moisture content

The information underlying the calculation algorithm regarding the calculation of the moisture in envelope elements are presented in this chapter. The calculations use real time weather monitoring data according to the first year of use. Figure 3 shows the total water variation of the wall over the analysed period:



(a) (b)

Figure 3. Moisture state of the wall insulated with existing (a) and with the new insulation system (b)

The performance of the ISPA was evaluated considering the difference in emissions generated by the studied building in both insulation cases.

When considering a relatively constant rockwool volume, the thicknesses of the panels according to the ISPA design are increased from 150 mm to 235 mm for the exterior walls and from 250 mm to 581 mm for the upper slab. Table 1 shows the physical and thermal properties of the insulation panels according to the calculation hypothesis:

Table 1. Volumul de izolație și proprietățile termice ale izolației amplasate la pereții exteriori și planșeul superior în cazul unui panourilor de izolație 600 x 1200 mm

Insulation system	Layer		d_{ins} (mm)	Insulating volume per panel (m3/m2)	$R_{insulating\ layers}$ (m2·K/W)
	description	layers in cross-section			
exterior walls					
EIS (150mm)	solid	1	150	0.208	3.839
ISPA (235 mm)	solid layers	6	20	0.167	5.600
	supporting frame	5	23	0.040	
upper slab					
EIS (250 mm)	solid	1	250	0.347	6.399
ISPA (581 mm)	solid layers	12	20	0.333	13.840
	supporting frame	11	31.0	0.059	

4.4.12 The influence of the ISPA on the thermal bridges

According to the preliminary results, the influence of the new insulation system based on several air chambers on the linear thermal transmittance coefficient is between 1.75-24.06% in comparison to the existing insulation. The leading variation is visible to the attic (24.06%). Here, the insulation thickness is the highest (250 mm and 581 mm) and the difference between the insulation panels is more evident. The calculation was carried using a designed software – HEAT3 [12].

5. LCA case study building

The chapter presents the LCA concept, the standards, regulations and the data basis used during the present LCA [14-19].

5.1 Basic assessment information

To ensure the credibility of the results, the validation of the software OneclickLCA [10], from the technically and scientifically point of view, is carried out by a certified entity.

5.2 Basic building data used in the LCA assessment

The input data used during the LCA calculation is presented. The chapter contains information regarding the processes and materials which contain embodied emissions attributable to the case study building.

5.3 Harmful emission generated during operation stage

The chapter contains the estimation of the emissions generated during operation stage of the building according to the theoretically determined energy demand.

5.3.1 Lightning of the school building

The electricity characteristics, i.e. that of the electricity grid in Romania, are presented along with the input data for the electricity demand of the case study building.

5.3.2 Heating

The heating system of the case study building is presented. Table 2 contains the electricity consumption attributable to the heating of the case study building.

Table 2. Emissions generated by the consumption of electricity

Resource	Quantity [kWh]	tCO_2eq	Comment
Electricity Romania	20431	609 t – 18%	IEA2019

5.3.3 Mechanical ventilation

The subchapter contains the input data for the mechanical ventilation used for the LCA of the case study building.

5.3.4 Hot water consumption

The chapter contains the input data for the hot water demand of the case study building.

5.3.5 Additional construction site operations

The chapter contains the input data of the additional operations attributable to the construction site used for the LCA of the case study building.

5.4 Characteristics of building materials

The subchapter contains the input data of the emissions embedded in the building materials of the case study building.

5.4.1 Service life periods

The LCA of the case study building was conducted according to the service life periods provided by the designed software [10].

5.4.2 Amount of building materials

The subchapter contains the calculations of the embedded emissions according to the building materials attributable to the case study building. The increase of the insulation quantity in case of the upper slab is attributed to the additional material contained by the ISPA. In case of the walls, the difference between the insulation systems is less than 0.1%. To highlight the additional volume that must be transported in case of the ISPA, the transport distance was increased with 50%.

5.5 Embedded emissions according to the insulation systems

The comparison between embedded emissions of the two insulation systems according to EN-15978 [11] is determined at 7,623.72 kgCO2eq for EB with 6.7% less than the ISPA system, 8,157,38 kgCO2eq.

5.5.1 Transportation to site

The chapter comprises the emissions attributed to transport to site according to the LCA of the two insulating systems. In case of the emissions generated by the transportation to site, the difference between the two insulation systems is estimated to be 322.86 kgCO2eq with 60.5% more emissions generated by the ISPA.

5.5.2 Construction/installation process

The additional emissions implied by a more complex construction process are not taken into consideration during this research. Accordingly, the emissions generated by the construction/installation process are considered equal for the purpose of this study.

5.5.3 Maintenance and material replacement

No specific tests were performed on the maintenance and replacement phases of the new system but nevertheless, all studies performed regarding the physical characteristics foresee a similar behaviour of the insulation systems. Therefore, it is assumed that they have similar emissions generated during maintenance and material replacement.

5.5.4 Energy use for heating during operation phase

The energy consumption according to the operating phase of the building insulated with both the EIS and the ISPA is theoretically determined. To validate the accuracy of the theoretically calculated consumptions, the real-time measurements performed by the design team are presented, along with in Table 3. According to theoretical estimates, during the building operation phase, the energy demand in the ISPA case is 15.05 kWh/(m2·year), with 35.5% lower than those generated in the EIS case, 23.35 kWh/(m2·year).

Table 3. Energy demand during operation phase

Type of Insulation		EIS	EIS	ISPA	Type of Insulation
Determination Type		Real Time Measurement	Theoretically assessed		
Energy consumption	$kWh/m^2 \cdot year$	21.24	23.35	Energy consumption	$kWh/m^2 \cdot year$
	kWh/year	74,340.00	81,725.00	81,725.00	kWh/year

The emissions of the building were estimated under the assumption that the building would be located in the five different national climate zones. The estimates are presented in Tabel 4:

Table 4. Energy consumptions for heating according to the national climate zones

Type of Insulation		EIS	ISPA
Climate zone II (Salonta)	$kWh/m^2 \cdot an$	23,35	15.05
	kWh/an	81,725.00	52,675.00
Climate zone I (Bucuresti)	$kWh/m^2 \cdot an$	22,70	14.63
	kWh/an	79,448.00	51,202.00
Climate zone III (Cluj-Napoca)	$kWh/m^2 \cdot an$	23,82	15.35
	kWh/an	83.375,00	53.725,00
Climate zone IV (Brasov)	$kWh/m^2 \cdot an$	24,16	15.57
	kWh/an	84.574,00	54.495,00

Climate zone V (Miercurea Ciuc)	$kWh/m^2 \cdot an$	25,07	16.2
	kWh/an	87.752,00	56.700,00

5.5.5 End of life. Demolition stage

The emissions attributed to the end-of-life stage are similar in the case of the two analysed cases. The limited effect of the ISPA is caused, as expected, by the similar content of solid insulative material.

5.6 LCA final results of emissions according to the analysed cases

The final results divided by each impact category according to EN-15978 are presented in this chapter. The reduction in embedded emissions increases with increasing service life. This is caused by the fact that, in the case of a longer service life, the proportion of emission attributed to the operation phase increases with regard to the total embedded emissions.

For instance, if we consider a 50-year lifetime, the reduction is between 3.21% in case of the total use of primary energy and 1.52% in case of POCP.

5.7 LCA final results according to manufacturing and operation (service life 50 years)

According to the overall LCA of the case study building, over a lifecycle of 50 years, the HSB has a total GWP of 3.556,109.41 kgCO2eq. The emissions saved by the innovative insulation system in comparison to the EIS are counted to 53,742.50 kgCO2eq.

As expected, compared to other school buildings, the emissions embodied in the case study building are up to 34.4% smaller compared to school buildings with common structure (concrete, concrete and masonry).

5.8 Economic sustainability assessment

The calculation of the global cost implies the sum of all the operations and initial costs, all of which referred to the starting year of the analysis. In addition to costs, the discount rate, price evolution, and the analysis period are considered during the calculation.

5.8.1 Economic sustainability assessment

The calculation of the payback period for the ISPA was determined to three years.

6. Conclusions. Personal contributions and future research directions

6.1 Conclusions of the research programme

The conclusions of the findings are as follows:

1. The optimum insulation thickness of the air layers is reached when the Rayleigh number approaches but succeeds the 1200 limit for vertical air layers and 1500 for horizontal air layers.
2. The laboratory investigations show slightly higher combined thermal conductivity of the ISPA compared to the existing insulation system with approximately 6.9%, from 0.03907 W/(m·K) to 0.04196 W/(m·K).
3. The thermal resistance of the exterior walls is improved by over 45.32% from 4.28 to 5.67 (m2·K)/W and in the case of the upper slab by more than doubled from 5.3 to 11.6 m2·K/W. These improvements of the thermal insulation properties were achieved with similar material consumption. The embedded CO2 emissions generated during the manufacturing stage were estimated to 7,623.72 kgCO2eq for the existing insulation and 8,157.38 kgCO2eq for the experimental insulation system.
4. The use of the new system (with air layers) determines an increase of insulation thicknesses comprised between 63% (wall) to 232% (upper slab) compared to the standard insulation system.
5. Compared to the standard rockwool insulation system of a high school building built to

passive house standards, when using the insulation system based on parallel air layers, the energy consumption is reduced by approximately 35%, from 23.35 kWh/m2year to 15.05 kWh/m2year.

6. The more complex manufacturing process is expected to produce additional emissions.

7. The additional emissions generated are expected to be saved during the first year of operation because of lower energy demand.

6.2 Personal contributions

- Study and synthesis of a large number of research papers;
- Development of a strategy and procedure to process a large amount of data registered by the monitoring system;
- Analysis and interpretation of the monitored data processed;
- Generating custom input data to perform laboratory simulations;
- Development of a complex building energy model, based on the real operational conditions;
- Establish a calibration procedure of the building simulation calculations in order to obtain simulation results that comply with the real measured energy performance;
- Investigate the influence of different changes of the innovative insulation system on the energy performances of the case study building;
- Optimisation of the innovative insulation system according to each national climate zone;
- Evaluate the reduction in emissions and material use in the case of the ISPA versus EIS.

6.3 Future work

The author proposes the following future research activities to be pursued:
1. Statistical processing and analysis of recorded monitoring data.
2. Monitor the new insulation system under real-time conditions.
3. Inventory the reduction in energy consumption and emissions generated over time.
3. Extend the implementation of the new insulation system to other buildings.
4. Continue the study of the improvement options of the new insulation system.
5. Assess the influence on the production, transportation and disposal cost.

6.4 List of publications

The list of the written papers is as follows: The results of experimental studies and research were disseminated through following scientific publications:

- **R. C. Ene**, S. Brata, I. Boros, D. Dan, ”Effect of inserted parallel air chambers in rockwool and polystinrene insulation panels”, Journal of Environmental Protection and Ecology, Vol. 21, Pag 202-210, May 2020 (ISSN 1311-5065), WOS:000531885700024
- **R. C. Ene**, S. Brata, I. Boroș, R. Chendeș, D. Dan, "Theoretical Study on the Effect of Parallel Air Chambers Embedded in Rockwool Panels on the Energy Consumption of a Low-Energy High School." Sustainability 14.12 (2022): 7425, WOS:000816824100001
- S. Brata, **R. C. Ene**, D. Dan, ”Low-energy school building – Effect of 2D vs. 3D steady-state simulation of thermal bridges”, CONFERINŢA NAŢIONALĂ TEHNICO-ŞTIINŢIFICĂ (cu participare internaţională) “Tehnologii Moderne pentru Mileniul III” - a 18-a ediţie - ORADEA, ROMANIA, APRIL 05-06, p123-128, 2019 (ISBN: 978-88-87729-41-2). WOS:000617030100021

- S. Brata, **R. C. Ene**, D. Dan, ”Analysis of the linear thermal coefficients according to multiple insulation systems”, CONFERINŢA NAŢIONALĂ TEHNICO-ŞTIINŢIFICĂ (cu participare internaţională) “Tehnologii Moderne pentru Mileniul III” - a 18-a ediţie - ORADEA, ROMANIA, APRIL 05-06, p167-172, 2019, (ISBN: 978-88-87729-41-2). WOS:000617030100028

- **R. C. Ene**, S. Brata, D. Dan, ”Life Cycle Assessment, an integrated vision to energy efficiency in the building industry” Chapter for "Energetics Perspective on the Environmental and Human Impact of Buildings" - Echivalat din capitol de carte in Springer Tracts in Civil Engineering ISBN 978-3-030-57418-5/ ISSN 2366259X, p313-340, BDI- SCOPUS doi:10.1007/978-3-030-57418-5_12

- **R. C. Ene**, S. Brata, D. Dan, ”The insulating façade system with parallel air chambers”, Global and Regional in Environmental Protection (GLOREP) 2018 Conference, Timisoara 15-17 November, Timișoara, (Conference Proceeding Editura Politehnica, Available online: https://glorep.upt.ro /resource/Glorep2018.pdf) pp. 63-67.

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