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TECHNICAL UNIVERSITY OF CIVIL ENGINEERING BUCHAREST
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THESIS
SUMMARY

ASPECTS REGARDING THE INTERIOR COMFORT AND THE PERFORMANCE OF THE BUILDINGS USING PASSIVE SYSTEMS

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SUMMARY

1. Introduction

Globally, in the last twenty years, the growth of the exploitation of conventional natural resources at an unprecedented rate, as a result of the increasing trend of the demand for energy use at the final consumer, consequence of population growth and economic and social developmen, generated in the scientific, economic and decision-making challenges on two crucial issues:

- the risk of depletion of the planet's natural resources;
- the massive impact that primary energy consumption has on the environment, through greenhouse gas emissions regarding the destruction of the ozone layer, global warming, climate change, etc., (Stowell et al., 2017, Thomas et al., 2014).

At the level of the European Union, the energy used in buildings represented in 2016 approximately 40% of the final energy consumption and almost 55% of the total electricity consumption, of which the largest share is represented by residential buildings, about two thirds of it.

An efficient solution to increase the energy performance of buildings and thus reduce primary energy consumption in buildings involves the adoption of passive principles promoted by the standard "Passive House which has become a reference standard, demonstrating its global viability and its implementation in The national energy strategy in the field of new building construction and those that will enter the process of major renovation.

The importance of the subject approached

The opportunity and need for the topic was generated by the general framework (summary) which currently deals with the rehabilitation of the existing building stock at national level, without having a horizon (target) of the level of energy performance to be achieved, reason to brings to the fore the ways to improve the energy performance of buildings by researching and implementing passive constructive and functional systems.

The purpose of the research and the proposed objectives

The main objective of the scientific research within the Project of the Scientific Research Program is to study the passive principles underlying the design, execution and evaluation of low energy houses, promoted by the Passive Houses standard, and the application of these strategies to buildings being built or rehabilitates in order to improve their energy performance.

The content of the doctoral thesis

The first chapter presents the introductory aspects of the global situation regarding the energy consumption intended to ensure the utilities of residential buildings, highlighting the main regulations that establish the guidelines in the field of energy efficiency of buildings.

Chapter 2 presents the theoretical aspects underlying the heat transfer processes encountered in the components of the building envelope and the calculation method in non-stationary thermal regime.

Chapter 3 reviews the main directives, regulations and technical regulations at European and national level in the field of energy efficiency of buildings.

Chapter 4 treats the issue of passive houses, presenting the basic principles of passive houses, the energy performance of the first prototype building, their evaluation criteria, design / evaluation software specific to passive houses as well as results of scientific research projects to validate these principles.

Chapter 5 deals with the movement of air inside a passive house, through the numerical simulation of air distribution in a living space and open space kitchen, in the initial design and final construction of the building, in order to optimize the distribution air jets, performing the analysis of indoor thermal comfort for the characteristic areas frequented by occupants.

Chapter 6 presents and analyzes the qualitative and quantitative results obtained from the numerical simulation of heat transfer through linear structures of linear thermal bridge type present in the composition of the building envelope examined, using passive thermal efficiency systems.

The last chapter presents the general conclusions for the issues addressed in the previous chapters based on the results obtained, the dissemination of this and the perspectives of scientific research in this field.

2. Buildings thermotechnics

Generalities

Building thermotechnics investigates the processes of heat and mass transfer (of water vapor), through their component elements, as well as the effects that these processes have on the conditions of indoor microclimate, hygiene and comfort of occupants, but also on thermophysical stability and mechanical of their constructive elements, (Ștefănescu, 2009).

Fundamentals

The main fundamental notions used in the theory and applications related to the study of heat transfer phenomena through the constructive elements of buildings are: temperature, temperature gradient, temperature field, isothermal line or temperature curve and isothermal surface. The physical quantities characteristic of the examined structures evaluated in the heat transfer processes are: heat flux or heat flow (Q), expressed in W, unit heat flux or heat flux density (q), expressed in W/m^2, global thermal resistance in the field expressed in m^2K/W, the overall heat transfer coefficient in W/m^2K, (Ghiaus, 2003).

Thermal bridges

The areas of the building elements, which have an increased thermal permeability to the rest of the element, causing the heat transfer to intensify by changing the amount of unidirectional heat flow transferred due to the structural or geometric composition, are called thermal bridges, (Ștefãnescu, 2012).

At the level of the components of the building envelope, the linear thermal bridges characterized by the linear thermal transfer coefficient (linear thermal transmittance) expressed in W/mK, produce direct hygrothermal consequences on heat transfer, changing the alignment of isothermal surfaces, thermal flux lines and interior surface temperatures from those in the current field.

3. Energy efficiency regulations

European regulations

The Kyoto Protocol is the first legal instrument in the world to establish legal constraints to monitor greenhouse gas (GHG) emissions and reduce pollutant emissions for industrialized countries by at least 8% during 2008- 2012 compared to 1990, followed by a series of directives setting target levels for reducing carbon dioxide (CO2) emissions by increasing energy efficiency in the European Union.

At European level, the main normative acts developed and issued in order to increase the energy performance of buildings were: Directive *2002/91/CE* (Energy Performance of Building Directive – EPBD), Directive *2009/28/CE* (Renewable Energy Directive – RED energia regenerabilă), Directive *2010/31/UE*, a („reformation EPBD" - nearly Zero Energy Buildings - nZEB), Directive *2012/27/UE* (Energy Efficiency Directive – EED- renovation of buildings to high energy efficiency standards), Directive 2015/1513/EU, - use of energy obtained from RES, and Directive (UE) 2018/844 on the quality of prosumer of newly built buildings.

Național regulations

The main normative acts in the field of energy efficiency at national level regarding the thermal rehabilitation of the existing built fund and the stimulation of thermal energy saving are: G.O. no. 29 / 31.01.2000 for the rehabilitation and thermal modernization of the buildings and related installations, G.O. no.174 / 09.12.2002 for the establishment of special measures for the thermal rehabilitation of multi-storey residential buildings and related installations, Law no. 372/13 of 2005, on the energy performance of buildings in relation to outdoor and location climatic conditions, Law no. 220/2008 for establishing the system for promoting the production of energy from renewable energy sources, G.E.O. no. 18/2009 on increasing the energy performance of apartment buildings, Methodology for calculating the energy performance of buildings, Indicativ. Mc 001/1-6-2006-2013, The norm regarding the thermotechnical calculation of the construction elements of the buildings, ind. C107/1-7-2005, as well as a series of guides and framework solutions for the thermo-hygro-energetic rehabilitation of the envelope of existing residential buildings.

4. Passive building energy

In accordance with the principles underlying the theory stated by the Passive Haus Institute (PHI) in Darmstadt: "A passive house is a building for which thermal comfort, according to ISO 7730, can only be achieved by post-heating or post-cooling the fresh air mass, which is necessary to obtain sufficient indoor air quality conditions in accordance with DIN 1946, without the need for additional air recirculation", (Feist, 1993).

The first Passive House was built between 1990/91 in Darmstadt, Kranichstein, Germany, by a team of specialists conducting specialized research within the “Passive House Preparatory Research Project”, in close collaboration and consultation with professors Bo Adamson and Gerd Hauser, (passiv.de).

The results of the monitoring of energy consumption in the passive house in Darmstadt-Kranichstein confirmed that from an energy point of view, compared to a standard building designed according to the provisions of the German codes of that period, the annual demand for energy for heating has decreased sharply by up to 90%, for electricity by 30%, due to the use of energy-efficient household appliances and extra gas consumption for auxiliary equipment for heat production is lower by 15%, (Ebel și Feist, 1997).

The principles of the Passive House concept

The design and execution principles underlying the concept are: efficient thermal insulation (kop ≤ 0.15 W / m2K), efficient windows (kfer ≤ 0.8 W / m2K) removal of thermal bridges ($\psi \leq 0.01$ W / mK), tightness of tire elements ($n_{a\,(50\,Pa)} \leq 0.6\ h^{-1}$) and ventilation system with heat recovery (ηrec ≥80%). In addition to these basic conditions in the process of designing the passive house are adopted a number of strategies and measures called passive: the compact shape of the building, the orientation of the building, the use of shading systems, the passive preheating or pre-cooling of fresh air, the use of renewable energy sources and the use of energy efficient appliances, (passipedia.org).

Passive House design software

Within the research projects in the simulation stages of passive buildings in stationary heat transfer regime, a thermal load calculation procedure was designed, which later became a permanent calculation tool developed by PHI, extrem de util în fazele de proiectare, testare, evaluare și certificare a caselor pasive, called Passive House Planning Package - PHPP, to ensure the internal thermal comfort of the occupants.

Passive House certification criteria

In order to assess the specific performance of passive buildings, in accordance with the principles of the Passive House concept, PHI has established the certification criteria corresponding to the following standards: *Passiv House,* for new residential and non-residential buildings, *EnerPHit,* for existing buildings that are being rehabilitated (renovated) and *PHI Low Energy Building*, for low energy buildings that do not fully meet the criteria of the Passive House standard, (passiv.de).

For to guarantee a high level of energy performance, an optimal level of comfort, a high degree of user satisfaction, as well as protection against damage caused by condensation of structural elements and building closure, it is necessary to comply with the minimum requirements generally valid for those three standards on: *overheating rate of the building* - the indoor temperature should not exceed the value of 25˚C more than 10% of the year, without active cooling, and the superhumidity rate of the house - the absolute humidity should not exceed the value of 12 g / kg more than 20% during the year, without active cooling, respectively 10% with active cooling, (passiv.de).

National scientific research projects

In Romania, so far, several educational projects of scientific research in the field of passive buildings in the Romanian university environment have been initiated and developed: in 2011 the project "Passive houses adequate to the climatic conditions in Romania" with the participation of several institutions, developed within the POLITEHNICA University of Bucharest, in 2012 at the Polytechnic University of Timișoara, the building "Almost zero energy house and passive house - sustainable solutions for residential buildings" had as main objective the validation of principles and solutions for design and construction of buildings in Romania, to the standard of passive house and building with almost zero energy consumption and "EFdeN Energy Independent Solar Passive House", with a complex approach to energy independence and efficiency design in which passive house design strategies are correlated with bioclimatic exploitation strategies, active systems and strategies. (Catalina, 2015).

Ventilation methods for passive buildings

For energy-efficient buildings depending on the climatic conditions specific to the climatic zone, ventilation systems based on passive (natural) ventilation methods of the type: windcatcher or hygrore-adjustable may be adopted, containing specialized controls enabling airflow control, depending on the level of pollutant concentration and/or the level of hygrometry (Saadatian, et al., 2012, Jomehzadeh et al., 2017) and decentralized mechanical ventilation systems with single or double flow, respectively centralized-controlled with heat recovery.

Alternative energy for passive buildings

Analysis of need and opportunity efficient use of systems to exploit the energy potential of renewable energy sources, focused on three important aspects: technical-economic, regarding the investment costs necessary for the implementation of systems that use renewable energy sources for heating / cooling and domestic hot water, operating costs related to their use, in relation to the costs of exploiting the available classical energy sources and the impact of its use on the environment.

The comparative analysis of the different heating systems with the system that uses renewable energy, based on the air-water heat pump was performed through the specialized application NIBE DIM SE, having as object of study an existing residential building, energy passively certified by PHI.

The simulation resulted in: annual reduction of energy consumption, operating costs between, amortization of the investment over the life of the system and reduced the carbon footprint of the building on the environment.

5. Air movement in mechanically ventilated rooms

The way in which the architecture of the designed ventilation spaces and installation, as well as the arrangement of furniture proposed by the designer influences the distribution of air flows through the analyzed spaces, with direct implications on occupant comfort, was achieved through numerical modeling and simulation of air distribution inside a passive houses in the initial and final design phases of the building.

Through CFD (Computational Fluid Dynamics) numerical modeling and simulations, with the help of the specialized software COMSOL MULTIPHISYCS, it was proposed to analyze globally and locally the air flow through an established field of interest, in order to verify the ventilation solution adopted in order to improve the air distribution in the analyzed space.

Building description

The object of study of the air flow analysis is a single-family home, located in Cluj-Napoca, 31 Vânătorului Street, consisting of basement, ground floor and first floor, designed in compliance with the basic principles of the Passive House standard.

The component elements of the building envelope, highlighted in the characteristic section of the analyzed building have the following characteristics: external walls: k_{op} = 0,125 W/m^{2}K, floor - k_{fl} = 0,111W/m^{2}K, joinery-frame: k_{fr} = 0,79 W/m^{2}K, glazing: k_{gl} = 0.51 W/m^{2}K, roof / terrace: k_{roof} =0.1 W/m^{2}K.

Physical model geometry

The field of interest (calculation / working area) for modeling and numerical simulation, which constituted the field of analysis is located on the ground floor of the building and includes:

- the kitchen located on the N, having: h = 2,40m and six exhaust grilles,
- the living room located on S, having: h = 3.05m, and two entrance grilles
- the connecting hall between them, having h = 2.70m.

The configuration of the physical models of the analyzed domain was made for two distinct cases: case 1 - without the furniture objects proposed by the architect in the analyzed domain and case 2 - with the furniture objects proposed by the architect in the analyzed domain.

The simplified working hypotheses considered were the following: the working fluid through the calculation range is dry air with T20 = 293.15 K, isothermal jet, adiabatic system (there is no heat and mass transfer, but only impulse), incompressible Newtonian fluid (speeds, low pressures - the compressibility factor does not intervene), the mass forces are neglected (there are no pressure differences caused by the gravitational field) and without internal heat sources in the analyzed field.

Numerical model configuration

For the modeling and simulation of air flow through the simulation field was used the application COMSOL MULTYPHISICS module "Chemical Engineering", section "Turbulence Flow", model "k-ε Turbulence", whose equation of motion is the Navier-Stokes equation of the form:

$$\rho \frac{\partial u}{\partial t} - \eta \nabla^2 u + \rho \cdot (u \cdot \nabla) \cdot u + \nabla_p = F, \ (\nabla \cdot u) \qquad (1)$$

where: η - dynamic viscosity in Ns/m^2; ρ - density in kg/m^3; u - speed in m/s; p - pressure in N/m^2; F- volumetric-gravitational force in N/m^3.

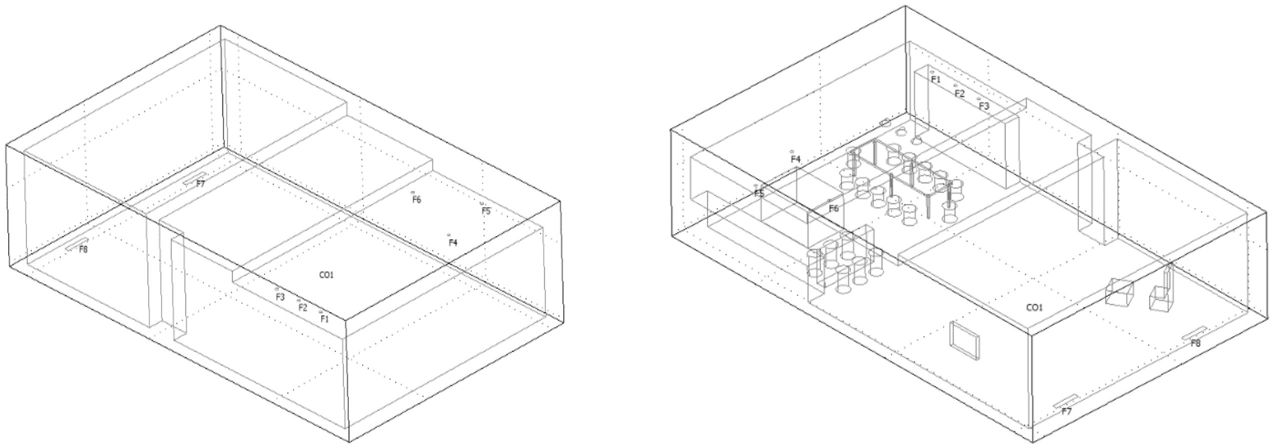
Uniqueness conditions

For the numerical simulation of the air flow through the working areas considered in the preliminary phase of processing the input data, uniqueness conditions are imposed: formed in turn from initial conditions (constant temperature, steady state, balanced ventilation, ($\dot{V}_{intr} = \dot{V}_{extr}$), the volume flow of fresh air introduced is equal to the volume flow of extracted air and the boundary conditions: the delimiting elements of the range were considered closed border, NO SLIP - the layer of air in contact with the wall surface, adhering to it, v_0=0, the furniture objects were extracted from the simulation field, in the volume occupied by them only air was considered, the inlet and outlet grilles are considered open borders, the velocities of the freshly introduced air jet were considered.: v_1 = 0,1 m/s și v_2 = 0,2 m/s, volume flows of fresh air introduced: $\dot{V}_{1int}$ = 86 m^3/h și $\dot{V}_{2int}$ = 172 m^3/h.

Simulation domain

The configuration of the simulation domains resulting from the entry of input data and the unique conditions on the internal and external borders of the simulation subdomains corresponding to the two cases considered is shown in Figure 1.

The air volumes related to the simulation domains resulting for the two analyzed cases are: $V_{1,aer}$ = 278m^3 - (for case 1) and $V_{2,aer}$ = 271m^3 - (for case 2).



a) Case 1 – without furniture b) Case 2 – with furniture

Figure 1: 3D Simulation domain

Discretization of simulation domain

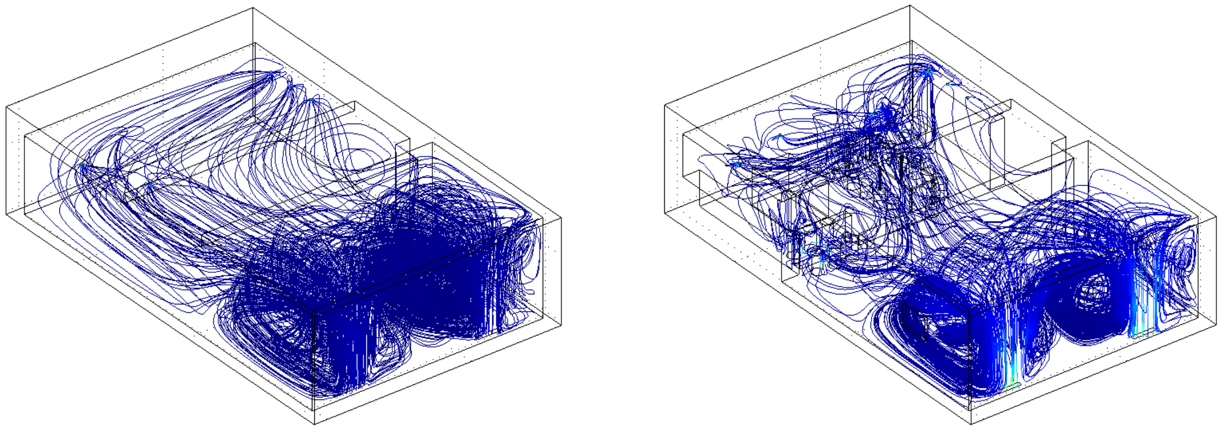
Discrediting the simulation domain was done by adopting the finite element method, and the resulting nodal networks are composed of 24,089 elements in the case without furniture and 34,497 elements in the case with furniture.

Flow simulation initial project

The global and local evaluation of the working fluid flow through the simulation field, in the case of the initial project was performed for the two considered cases, in the conditions of the speeds of the fresh air jets introduced with the imposed values of 0.1 m/s and 0.2 m/s, from the point of view: qualitatively by the distribution of current lines and velocity vectors and quantitatively by the distribution of velocity contours.

Global qualitative and quantitative analysis

Analyzing the overall qualitative flow of the working fluid, in the design phase, materialized through the distribution of power lines, figure 2, shows that in the adjacent area of the intake grilles a turbulent movement of air arises which intensifies with increasing speed of introduction his. The presence of furniture proposed by the architect leads to changes in the configuration of air vortices, and in the kitchen area there is an uneven distribution of current lines due to the presence of furniture in this space, resulting in a recirculating movement in the upper part of the dining area.



Case 1 (v_1= 0,1 m/s, $\dot{V}_{1int}$ = 86 m^3/h)   Case 1 (v_2= 0,2 m/s, $\dot{V}_{2int}$ = 172 m^3/h)

Figure 2: Current lines distribution

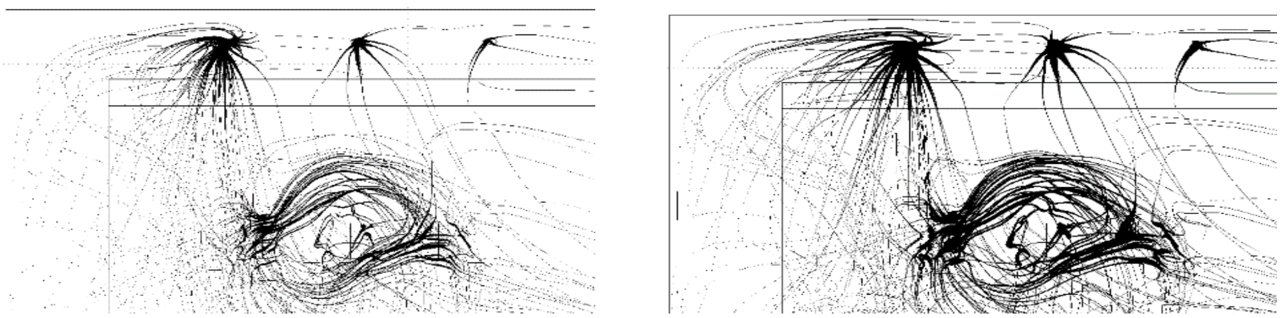
In order to highlight the existence of areas where possible perceptions of local discomfort of users, generated by the speed of air currents, the global analysis of the working fluid flow through the distribution of velocity vectors through the simulation domains for two section planes was performed located at 0.8 m and 1.2 m from the floor. Quantitative analysis of flow through velocity contours revealed the presence of the ascending air jet at the inlets that can generate thermal discomfort in the southern area of the simulation range.

Isothermal air flow local analysis

Similarly, from a quantitative and qualitative point of view, the local analysis of the air movement in two horizontal reference plane planes corresponding to the fresh air intake and exhaust air grids was performed for the air jet velocities introduced by: 0,1 și 0,2 m/s.

The distribution of the speed contours differs in intensity from the outside to the inside of the grilles, and in the central area of the air passage section speed peaks appear higher than the average input speed, and in the presence of furniture the “amplitude” of the speed contours is lower than in the version without furniture.

Above the kitchen table, there is an area, shown in Figure 3 in which the air is recirculated, which can cause local discomfort to the occupants of the building during the meal.



a) (v_1= 0,1m/s, $\dot{V}_{1int}$ = 86m^3/h)   b) (v_2= 0,2m/s, $\dot{V}_{2int}$ = 172m^3/h)

Figure 3: Current lines local distribution at the exhaust grids – Case 2

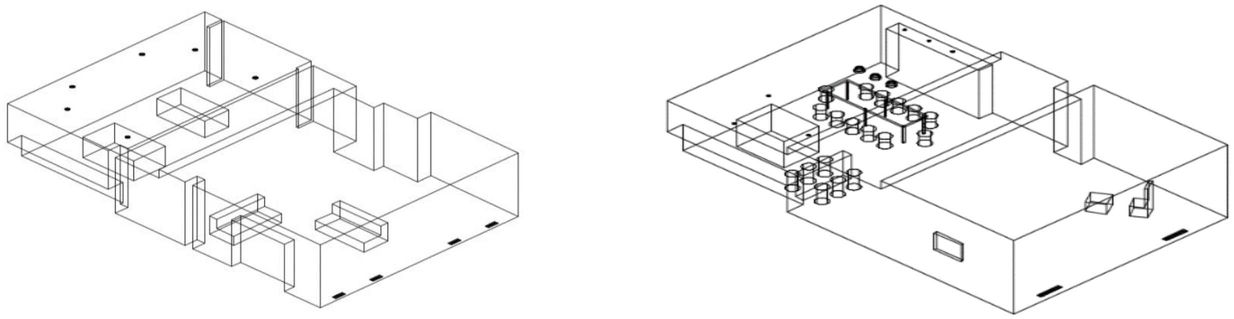
Flow simulation final project

At the stage of completion of the building, using data from the real construction of the building and the ventilation system redesigned it was carried out modeling and numerical simulation in order reconsideration flow isothermal air in the new area of real interest to see as compared with the situation efficient project solution

Real physical model

In comparison to the design for the new area (real) examined differences were observed constructive shape and dimensions that are required remodeling acesuia, the new numerical simulation result for the case of real (actual situation), figure 4, with the same volume of air inside.

In order to eliminate the turbulence in the area of the fresh air intake grilles, the non-uniformities and the recirculation areas in the kitchen area, the ventilation installation was reconfigured, changing the number of fresh air supply grilles, maintaining their section as well as the relocation of the waste air grilles from the kitchen space taking into account the dimensions and arrangement of the new pieces of furniture.

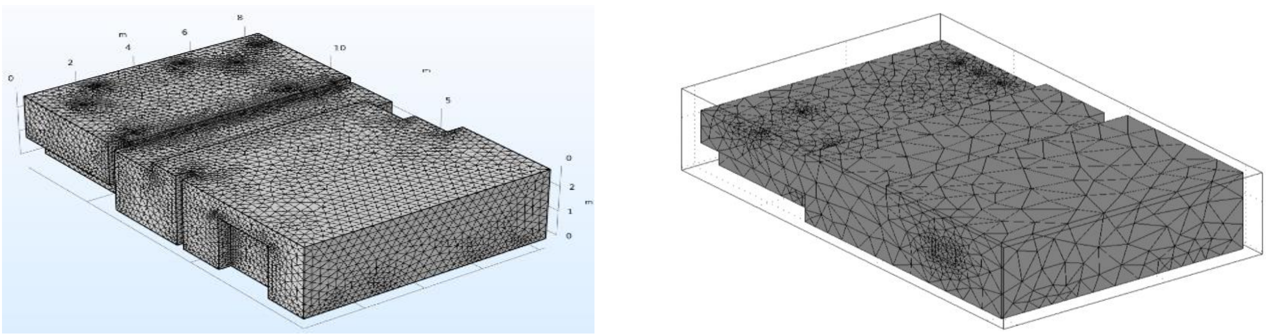


a) real situation b) initial situation

Figure 4: 3D Simulation domains

Discretization network real case

The real discretized numerical simulation domain, using the finite element method, presented in figure 5, has in composition 369,662 elements compared to 34,497 for the projected case.



a) situația reală b) situația inițial proiectată

Figure 5: Nodal network of simulation domain

Comparative analysis of isothermal air flow

Reanalyzing the isothermal air flow from a qualitative and quantitative point of view globally and locally by comparing the results of the simulation of the working fluid flow through the simulation fields related to the initially designed situation it was observed that the solutions adopted remedied the inconveniences generating local inconveniences due to the speeds of air currents in the living room and kitchen.

Thermo-aeraulic analysis of non-isothermal air flow

In order to perform the thermo-aeraulic analysis of the air flow in non-isothermal conditions through the real simulation domain, the modeling of the real interest domain and the numerical simulation of the coupled phenomena of air flow and heat transfer were performed. The quantitative global and local aero-aeraulic analysis of the interconnected phenomena was performed for the summer and winter situations through the distribution of the temperature field and the current lines within the simulation field.

Thermo-aeraulic analysis in the summer

For the summer situation, the distribution of the temperature field in a useful horizontal plane located at a height of 1.2 m from the lower limit of the simulation range, shown in Figure 6, as well as the distribution of the temperature field in a longitudinal vertical plane were analyzed passes through the center of the simulation range, figure 7, in order to identify areas where temperature variations are present that may cause local thermal discomfort to occupants.

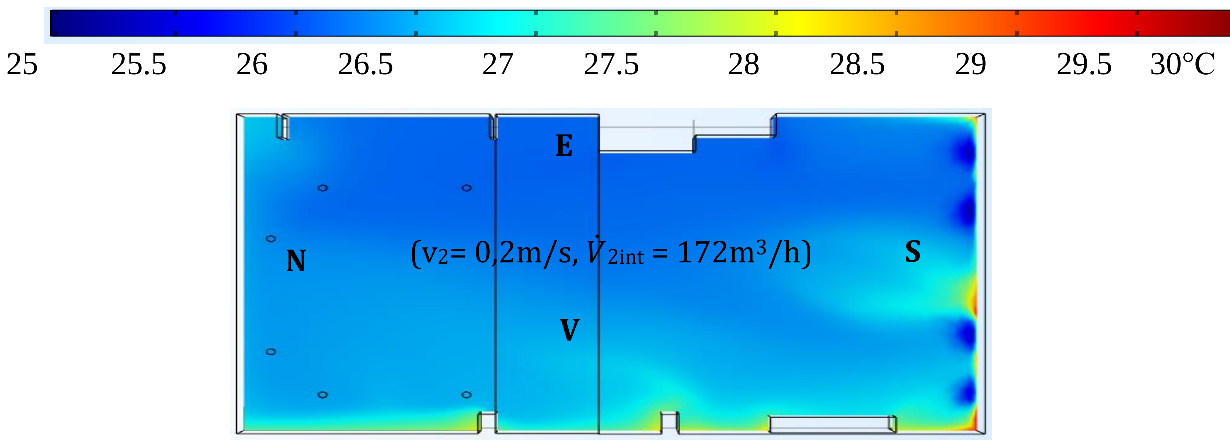


Figure 6: Temperature field distribution in the horizontal section in summer

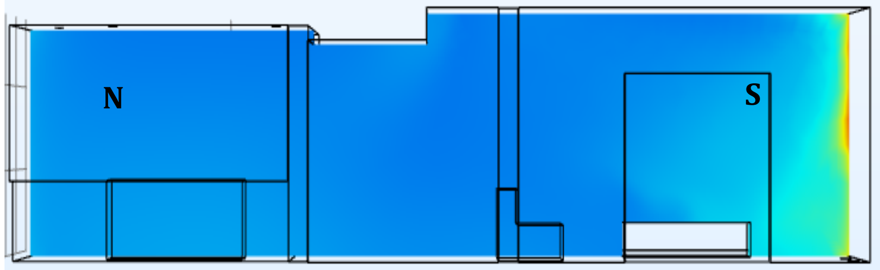


Figure 7: Temperature field distribution in the vertical section in summer

Thermo-aeraulic analysis in winter

Considering the same characteristic plans, the elements that can influence the thermal comfort were analyzed in the case of the winter situation, through the distribution of the temperature field, presented in figures 8 and 9.

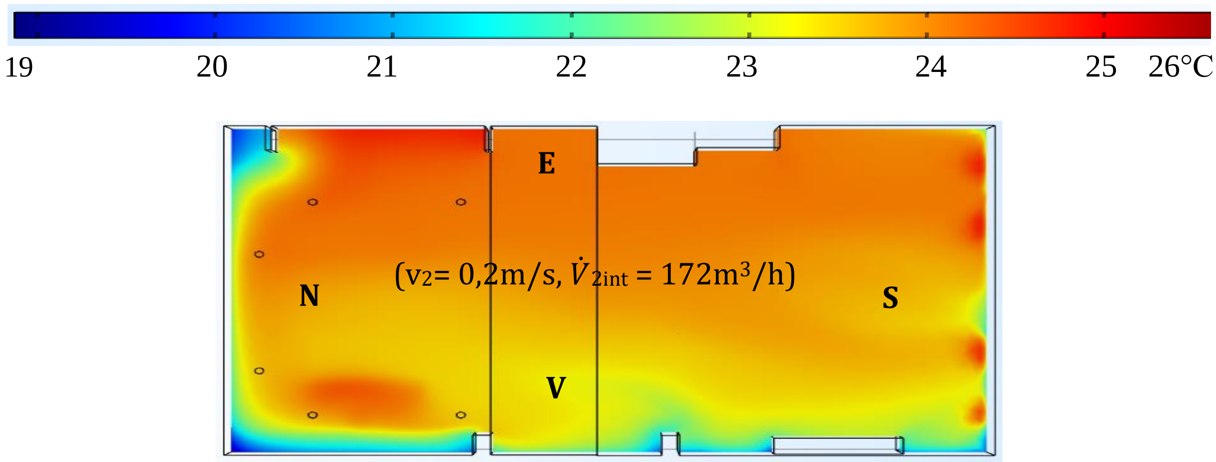


Figure 8: Temperature field distribution in the horizontal section in winter

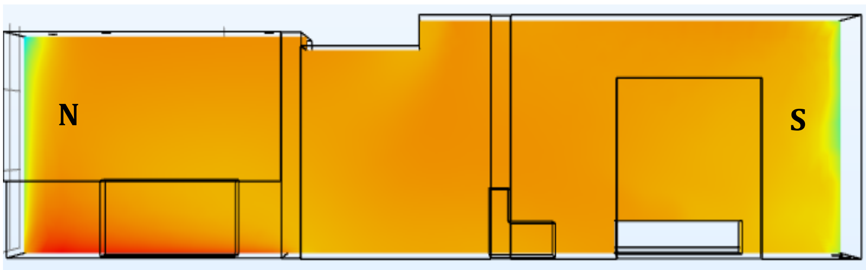


Figure 9: Temperature field distribution in the vertical section in winter

Thermal comfort analysis

In order to establish the category of thermal comfort in which the analyzed field can be included for the summer and winter situations, the determination and analytical interpretation of the PMV and PPD thermal comfort indices was performed, using the calculation procedure for the local evaluation of the thermal comfort, described in SR EN ISO 7730: 2006, based on the evaluation of the physical quantities in the post-processing phase of the results obtained following the numerical simulation.

6. Numerical modeling of thermal bridges

In order to demonstrate the impact that thermal bridges have on the energy balance of the building, the study of the thermal behavior of the components of the envelope of a building was carried out, in order to improve their thermal performance, through numerical simulation of heat transfer using the COMSOL MULTYPHISICS application, which allows the visualization of the two-dimensional temperature field and the evaluation of the total heat flow transferred and through the elements of the linear thermal bridge details, (Kotti, et al. 2017).

Geometry of physical models

During the construction of linear thermal bridges, seven types of details were defined that can be found at the level of the facade of a building, adopting a series of passively specific construction strategies to reduce/eliminate the dissipative effect of the transferred heat flux (heat loss) by closing the thermal bridge using energy passive systems and elements.

Uniqueness conditions

For the analyzed simulation fields, for each situation a series of conditions were adopted attached that define the particularities of the respective case, called uniqueness conditions (initial and/or at the limit, on the contour) as well as simplifying working hypotheses.

Among the simulated and analyzed details, a particular feature is the coupling detail between a transparent element (window joinery) and an opaque element (exterior wall), whose reference model is shown in Figure 10. In this case, measures were adopted for the thermal rehabilitation of the usual opaque elements used in practice, gradually up to energy passive measures and different assembly strategies of the existing transparent element as well as its replacement with an energy-efficient glazed system.

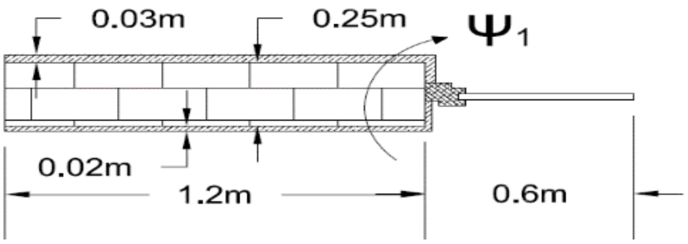


Figure 10: Coupling detail of exterior wall and window joinery in horizontal section

The configuration of the simulation subdomains of the numerical model in order to simulate the heat transfer through the simulation domain was done using the "General Heat Transfer" module, which uses the well-known law of heat conduction, of Fourier, for the calculation of heat flux, (comsol.com):

$$\dot{Q} = -\lambda \cdot A \cdot \frac{dT}{dx} \tag{2}$$

where: $\dot{Q}$ - the total heat flux transmitted by conduction in W; λ - thermal conductivity of the material in W/mK; A - cross-sectional area in m^2; dT/(dx) - temperature gradient in K/m.

Discretization of simulation domain

Using the finite element method, the discretization of the simulation domain and the automatic generation of the nodal network was performed, whose structure shown in figure 11 is composed of 9776 interconnected tetrahedral elements.

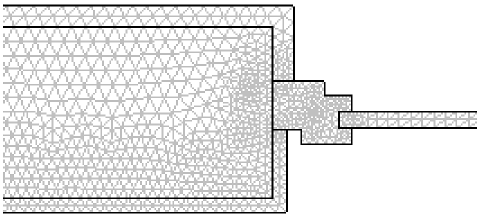


Figure 11: Discrediting network

Temperature field distribution

The qualitative distribution of the temperature field through the details of the linear thermal bridge specific to the analyzed couplings, is presented comparatively in figure 12 for the solutions: a) the reference physical model (existing situation), b) insulated exterior wall δ_{iz} = 10 cm, uninsulated window sill c) passive window mounted in the insulation field, δ_{iz} = 20 cm.

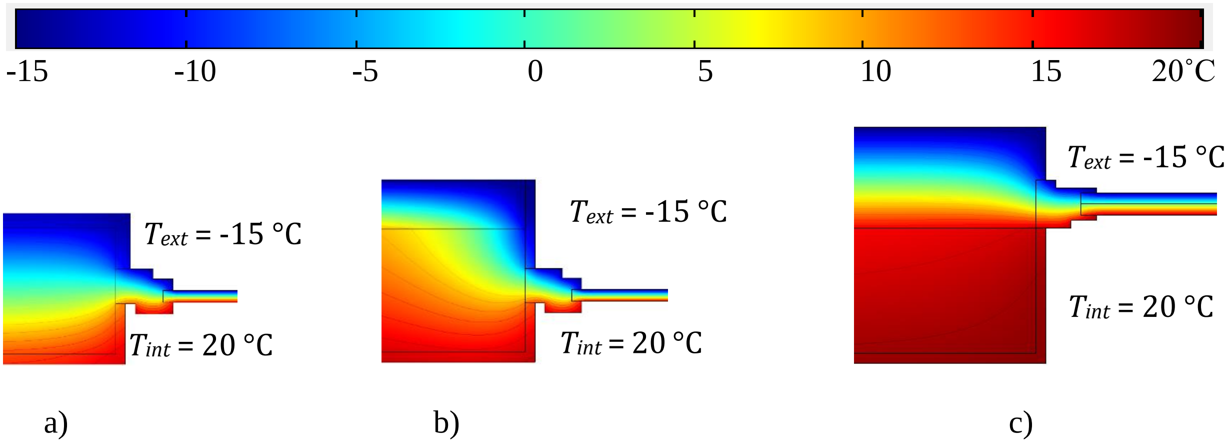


Figure 12: Temperature field distribution - Exterior wall and window joinery case (in horizontal section)

Unit heat flux distribution

The qualitative distribution of the unit heat flux transferred through the surface unit of the elements in the composition of the linear thermal bridge details, corresponding to the coupling between the outer wall and the carpentry, in vertical section is shown in figure 13.

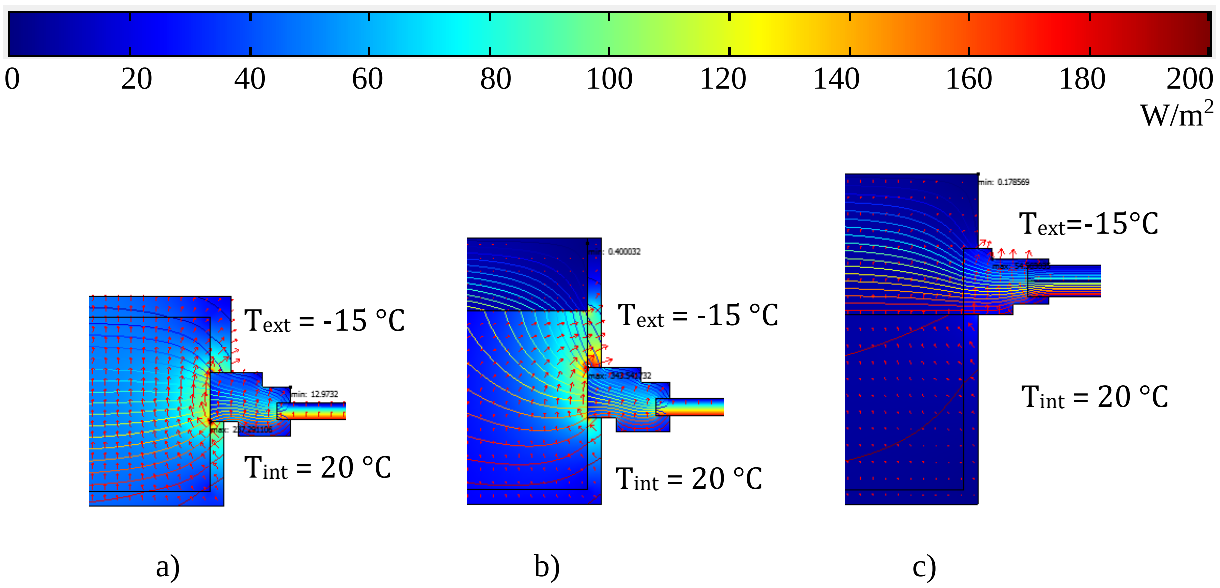


Figure 13: Unit heat flux distribution

Evaluation of heat loss through transmission

The quantitative evaluation of the heat losses by transmission through the envelope elements of the building facade was performed by determining the physical quantities characteristic of the heat transfer in stationary regime through its component elements (Bergero, 2018). The determination of the linear thermal transmittances, specific to the linear thermal bridges, was performed based on the estimated thermal flux following the bidirectional thermal field simulation process, quantified and supplied by the Comsol Multiphysics application and the unidirectional heat flow dissipated through the current field area of the components of the building facade, using the calculation procedure from the norm C107/3-2005.

The evaluation of heat losses by transmission at the level of the main facade was performed for three distinct cases the reference case (existing situation), the usual case of thermal rehabilitation and the case of the use of passive construction systems (specific to passive buildings).

Thermal and energetic analysis of the building

Based on the results obtained from the numerical simulation of the heat transfer through the linear thermal bridges, the thermal, energetic, economic and environmental analysis of the technical solutions for thermal rehabilitation of the analyzed building was performed, by adopting passive constructive systems and implementing renewable energy sources in order to optimize its energy efficiency, (Kaynakli, 2012) for identifying the optimal solution (the one with the best optimization balance for all criteria), and choosing the most suitable variant for the specifics of the modernized building, (Ascione et al., 2017, Shao et al., 2014).

Analyzing from the energetic point of view the performance of the rehabilitated building constructively and functionally through the prism of the amount of primary energy necessary to ensure the necessary consumption for all consumers of the building using the factors of conversion of final energy (at consumer level) into primary energy it was found that the measures adopted reached a minimum level of total specific annual primary energy consumption of 79.59 kWh/m^{2}year.

Impact of the use of the renewable energy source in terms of the amounts of CO_2 emissions emitted into the environment, using CO_2 emission factors, corresponding to each type of fuel used, attributed to the specific annual consumption of primary energy for the production of utilities, was estimated at 21 kg CO_2/m^{2}year.

7. Conclusions

Research conducted in doctoral studies on methods to improve the energy performance of buildings demonstrates the need and opportunity to adopt passively constructive and functional technical solutions to conserve thermal energy produced from indoor sources, reducing heat loss through direct transmission through building envelope elements and the use of alternative energy sources, for new buildings and for energy efficiency of existing ones that are being rehabilitated.

Personal contributions

Personal contributions on interior comfort and passive methods of improving the energy performance of buildings were made by researching the scientific literature on passive houses, mechanical ventilation methods with heat recovery and analysis of their specific thermal comfort, use of alternative energies for passive buildings and thermal, energetic and economic analysis of passively constructive and functional solutions for the rehabilitation / modernization of buildings.

Passive house energy

The results obtained in the scientific research projects initiated by PHI, have shown that the principles of the standard of passive houses are viable in all climatic zones, making possible the construction of new buildings and rehabilitating existing ones to the highest standard of energy efficiency, with reasonable costs throughout the life cycle of the building.

Alternative energies for passive buildings

In order to demonstrate the need and opportunity of implementing renewable energy sources, for energy-efficient buildings, from an energy and economic point of view as well as the impact of their use on the environment, a series of simulations were performed through the specialized application NIBEDIM.

The energy impact consists in the annual reduction of energy consumption with values between 73-80%, economically by decreasing the annual operating costs with values between 66-86%, and ecologically by reducing the amount of annual CO2 emissions with values between 74-80%.

Mechanical ventilation analysis of living spaces

Overall qualitative and quantitative analyzes in order to streamline the distribution of indoor air in the simulation area in the initial and final design phases of the ventilation installation have shown that the solution of reconfiguring the ventilation installation has led to the elimination of local inconveniences, obtaining a uniform air flow in the areas frequented by occupants.

The numerical simulations of the non-isothermal air flow for the summer and winter situations through the simulation field after the redesign of the ventilation installation allowed the evaluation of the physical quantities necessary to determine the PMV and PPD thermal comfort indices, in accordance with the evaluation criteria from SR EN ISO 7730: 2006, SR EN 15251: 2007, respectively of the Passive House standard for the assessment of the thermal comfort categories within the analyzed field.

The analysis of comfort indicators led to the conclusion that within the simulation field there are no areas in the simulation field that can generate local discomfort to its occupants generated by the speed of air currents or the temperature gradient. At the same time, it was noted that in order to maintain an optimal thermal comfort level in the analyzed area, it is necessary to adapt the introduced air temperature during the summer depending on the passive solar heat inputs through glazed surfaces and heat emissions from internal sources.

Thermal bridges numerical modeling

The analysis of the impact due to the presence of the existing linear thermal bridges at the level of the building facade was performed by simulating the behavior of the analyzed structures through the simulation and numerical modeling of the heat transfer through them, adopting a series of passively constructive strategies for the opaque and transparent elements of the building envelope, in order to reduce / eliminate the effects of linear thermal bridges.

An extremely important aspect observed during the simulations was that with the closure of the linear thermal bridges by ensuring the continuity of the thermal envelope applied to the opaque elements in the composition of the thermal bridge details, led to the increase of thermal stability of the analyzed structure and the considerable decrease of the transferred thermal flux with values between 35-87%, respectively of the linear thermal transmittance by up to 98%, compared to the existing situation.

At the level of the main façade it is found that the heat losses by direct transmission corrected with their effect increase by 29% compared to the neglect of their presence, decreasing by 67.84% in the case of thermal rehabilitation only of opaque elements. The solution of the rehabilitation of the opaque and transparent elements according to the requirements of the passive buildings generated the reduction by 87.48%. Of the heat losses by direct transmission corrected compared to the reference case

Thermal, energy and economic analysis rehabilitation solutions

For the constructive and functional rehabilitation of the analyzed building, the thermal and energetic analysis was performed, in which the energetic performances of the real building and of the reference building attached to the real building were examined. In order to improve the energy performance of the real building, two rehabilitation solutions were proposed and analyzed from an energy and economic point of view, using passive construction systems. Analyzing the results obtained for the actual building-specific energy indicators, the reference of the building rehabilitated by adopting the usual constructive solutions for heat insulation and the specific passive, energy modernization and it has been found that: the energy requirement for heating the building is reduced by up to 80%, in the case of the usual thermal rehabilitation solution, respectively 87.5% in the case of the passive house standard rehabilitation solution.

Starting from the real performance of the building in which the total specific annual consumption is 568.02 kWh/m^2 year, which places the real building in energy class F, by adopting the usual thermal rehabilitation measures to improve the thermal performance of opaque elements, we reach a total specific annual consumption of 175.24 kWh/m^2 per year, specific to energy class B. The imposition of specific heat insulation measures for improving the thermal performance passive elements of the building envelope opaque and transparent real consumption leading to a specific annual total of 59.36 kWh/m^2 year, resulting in a high building from a building reference.

Functional modernization of the thermal energy production system by implementing the system based on the ground-to-water heat pump, which uses the renewable energy of the soil, and which provides the thermal energy necessary to cover the thermal load for heating and hot water preparation has allowed to reduce the annual thermal energy consumption by 65% compared to the situation of passive constructive rehabilitation (the usual thermal rehabilitation solution), respectively by 92% compared to the real situation and the total specific annual consumption of primary energy by 60% compared to the passive thermal rehabilitation solution, respectively 90% compared to the real situation.

These primary energy savings have a direct positive impact on the environment by reducing the amount of pollutant emissions by 81% compared to the real situation and from an economic point of view by reducing energy acquisition costs by 87%, which allows the recovery of the investment made in the first half of the life of the implemented solutions. Based on the analysis of energy, economic and environmental indicators, it can be assessed that the impact of the use of passively constructive systems (specific to passive houses) of thermal energy rehabilitation of the building and modernization of the thermal energy production system, using solutions that incorporate renewable energy sources, the maximum level of energy performance is obtained, which allows the certification of the building at the level of building with almost zero energy consumption (nZEB), fulfilling the general objective of the research.

Dissemination of the results

Following the documentary research of the reports of the research projects developed by PHI, of the scientific materials from international databases on the issue of passive houses, of the dissemination reports, of the results obtained for the passive buildings under monitoring, of the energy performances and of the participation in the execution works of the passive houses, the first work entitled “Passive Houses –

Efficient and Sustainable Buildings" was published, published in the journal Romanian Journal of Building Services, vol.2, nr.1., 2017.

The results of the global analysis through numerical modeling and simulations of isothermal airflow in a space in front of a passive building, which is in the design phase, were disseminated during the first conference of the UTCB Doctoral School, held in Bucharest on October 26, 2018, where I participated with the paper: "*Influence of furniture arrangement on air flow distribution in open concept passive houses*", indexed ISI in E3S Web Conferences, vol.85, with DOI identification code: 10.1051/e3sconf / 20198501010.

The qualitative and quantitative local analysis of the isothermal air flow through the simulation field analyzed for the passive house in the design phase were disseminated during the international conference "Climate 2019", held in Bucharest between 26-29 May 2019, where I participated with the paper: "*Local analysis of airflow distribution in open concept passive houses*", indexed ISI in E3S Web of Conferences, vol.111, with DOI identification code: 10.1051 e3sconf/201911101019.

The results of the qualitative and quantitative analyzes of the impact of thermal bridges through modeling and simulation of heat transfer through the components of the building envelope on the heat demand of the building were disseminated during the second conference of the UTCB Doctoral School, held in Bucharest between October 25, 2019, where I participated with the paper:"Effects of thermal bridges on the heat demand of residential buildings".

Prospects of research

The research carried out and presented in this paper can generate new directions for evaluating the constructive and functional performances of buildings. A possible direction may be to extend the analysis of simulation and multizonal numerical modeling of air distribution throughout the building.

Also, another research horizon could be the realization through numerical simulations of an energetic passive window model capable of limiting solar inputs and maintaining stable comfort conditions for all climatic zones of the country.

A research objective with multiple implications in the direction of improving the energy performance of the constructive and functional elements of the building, the interior comfort and the impact on the environment may consist in carrying out the rehabilitation of a residential or public building using the basic principles of the Passive House standard, with the help of the PHPP application developed by PHI.

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