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ASSESSMENT OF THE ENERGY PERFORMANCE AND LIFE CYCLE OF BUILDINGS

PhD thesis – Summary
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Abstract

Achieving the global strategic environmental objectives requires firm and effective actions to reduce energy consumption in the construction industry. Investigating pilot projects of energy-efficient buildings through numerical modeling and measurements can be a way to refine technical solutions that improve the environmental impact of the built fund. Also, the evaluation of their behavior during their entire life cycle is fundamental for the validation of the proposed solutions. The paper is based on an energy efficient and high interior comfort school building in Romania, where a monitoring system has been implemented for the real time measurement of parameters that define energy behavior. Details of the technical solutions regarding the thermal envelope, building services, monitoring strategy, sensors and measuring instruments are presented. The energy performance of the building was evaluated by numerical calculation and the results are compared with the values of reference buildings but also with the values of measured energy consumption. Varying outdoor temperatures and operating patterns are the main causes of the difference between the calculated and measured values. The environmental impact is determined by assessing the carbon footprint of the construction phase and CO_2 emissions for 50 years of use. The global cost is determined by taking into account all costs from the beginning of the construction until the end of the considered usage period. Energy consumption, environmental impact and the global cost of the school building are compared to the values of reference buildings. Furthermore, the benefits of the energy efficiency technical solutions are highlighted.

Thesis chapters summary

1. Introduction

The chapter presents general aspects regarding the energy consumption of the construction industry, energy unit costs, motivation and objectives of this paper.

1.1. Energy consumption of buildings

At European Union level, in 2016, the final energy consumption of buildings was 434.80 Mtep, which represents 39% of the total consumption of the 28 member states [1]. In Romania, in 2019, the final energy consumption of buildings was 9.52 Mtep, which represents 42% of total national consumption [2]. Thermal energy represents 80% and electricity represents 20% of the total energy consumption. Non-residential buildings represent 5% of the total number of buildings, 10% of the total heated area and 19% of the total final energy consumption.

1.2. Existing legislative framework

Directive 2018/844/EU [3], amending Directives 2010/31/EU and 2012/27/EU, sets out the principles to be applied in order to meet the new main targets, namely: reducing global greenhouse gas emissions by at least 40% below 1990 levels by 2030, and by 80-95% by 2050. Law 372/2005 regarding the energy performance of buildings in Romania, republished and updated with Law 159/2013, Law 156/2016 and Law 101/2020, took over the provisions of EU Directives and established the principles to be respected in the development of the National Long-Term Renovation Strategy.

1.3.Global energy trends

Primary energy conversion factors express the amount of primary energy used to generate a unit of final energy, taking into account the characteristics of the industrial process of supplying energy to the final consumer. In Romania, the value of the electricity factor (2.62) [4] is a consequence of the share of primary energy resources in its production. In the case of energy consumption of buildings, the ratio between the conversion factor of electricity and that of natural gas (2.24) is an important factor in determining the energy source for heating and domestic hot water preparation. Conversion factors for each type of energy source are defined, that determine the equivalent amount of CO_2 emitted for each kWh of primary energy consumed. According to the Report "EU Energy in Figures 2018" [1], published by the European Commission for the period 2010 - 2016, CO_2 emissions in 2016 of EU member states was 3637.3 million tons of CO_2, and for Romania it was 75.9 million tons CO_2.

The evolution of the average unit prices of electricity in Romania over the last 13 years show an average annual increase of 0.85% [5]. In the first half of 2020 the unit price of electricity was 0.1422 Euro / kWh, VAT included. The unit price of natural gas in the same time period was 0.0324 Euro / kWh, VAT included [5]. Regarding the evolution of the unit price of natural gas in Europe between 2020 and 2030, the World Bank's estimates [6] imply an average annual increase of 2%.

1.4.Energy efficiency of buildings

This subchapter presents the existing state of studies and research activities in the field of energy performance of school buildings, thermal envelopes, building services, interior comfort, user behavior, numerical models, monitored data and life cycle assessment.

1.5.Motivation and objectives of the research

The main motivation of this paper is to carry out a pilot project that can be used as an example of good practice, from both an energy saving point of view, and for the quality improvement of the built fund.

The synthesis of the main objectives of the present thesis includes:

- Carrying out a pilot project of energy efficient educational building, both at design and at implementation level.
- Determining the theoretical energy consumption in accordance to the national calculation methodology, and to compare it with those of reference buildings.
- Implementation of a complex monitoring system for measuring the parameters that define the energy performance of the building and its interior comfort.
- Processing the data recorded by the monitoring system regarding real time energy consumption of the building, comparing it with the calculated theoretical values and identifying the sources of differences.
- Life cycle assessment of the school building.
- Propose changes to existing legislation and calculation methodologies based on research results.

1.6.General presentation of the thesis

This subchapter presents the content of the thesis, briefly describing each main chapter. The thesis is structured in seven main chapters and seven annexes, totaling 291 pages.

2. Energy performance of buildings

2.1. *Types of calculation methodologies*

The national calculation methodologies of EU Member States for the energy performance of buildings are based mainly on stationary calculation principles, using seasonal or monthly methods. With regard to the minimum performance levels of newly designed buildings, each Member State is free to set its own technical requirements, as long as the overall regional greenhouse gas reduction targets are met.

Among the standards dedicated to energy efficiency and interior comfort, the concept of Passive House [7] is the best known and used standard. This approach involves maximizing the use of numeric resources to achieve the most efficient and accurate result possible. The system for applying alternative methodologies also contains certification components that validate the compliance with the provisions of these standards by specialized organizations.

2.2. *National calculation methodology*

In Romania, the calculation of the energy performance of buildings is made in accordance with Mc 001/2006 [4], which was made developed on the provisions of Law 372/2006 and as a continuation of the technical regulation C107 - Norm regarding the thermotechnical calculation of building construction elements [8]. The methodology establishes stationary calculation procedures for determining the energy consumption of building services (heating, domestic hot water, cooling, mechanical ventilation and lighting). The results of the calculation procedures are expressed in final energy, primary energy and CO_2 emissions.

The proposal to change the methodology [9] expands the principles imposed by the EU Directives on improving the energy performance requirements of buildings, respectively by defining the concept of nearly zero energy building (nZEB). nZEB buildings are defined by a very high energy performance, with an energy consumption of almost zero that is covered by renewable sources produced on site or near the building in a proportion of at least 30%.

2.3. *Passive House Standard*

The constructive concept involves achieving an airtight envelope with high thermal performance, efficient use of internal and solar gains, and the provision of fresh air through mechanical ventilation systems. The automatic numerical calculation tool used to design Passive Houses [7] is the Passive House Planning Package (PHPP). Globally, the number of non-residential buildings with Passive House certifications is 782, of which the number of educational buildings is 303 [10].

2.4. *Monitoring systems*

Monitoring systems in the field of energy efficiency of buildings are mainly used in industrial applications, where energy consumption is a significant cost of the technological process. For civil buildings monitoring is limited to the use of total energy consumption meters, connected to data acquisition stations [11]. The data provided by these systems are used to establish usage strategies of the building or to justify investments that lead to energy consumption reduction. Also, the processed data resulting from monitoring actual consumptions of buildings is currently not a relevant factor in defining calculation methodologies.

2.5. *Life cycle assessment*

The long-term quantification of the level of negative effects of the construction industry on the environment can be achieved using life cycle assessment methods. The main stages of a life cycle include: raw material, processing, transport, use, end of life and recycling.

Buildings are complex elements whose numerical modelling involves data for a variety of materials and technological processes. Energy consumption during the usage of the building is the predominant factor for impact on the environment. The usage phase implies the definition of energy consumption, current repairs and maintenance work, over the considered lifetime. Most life cycle studies of buildings consider a lifetime of 50 years or an end of life scenario. The use of resources, the influence on human health and the deterioration of the environment are the main global impact categories for which results can be determined.

2.6. *Calculation methodology and data used*

The calculation of the energy performance of the analysed educational building was performed in a stationary regime, in accordance with the Mc 001 methodology, and the climate data is that of Oradea. A usage scenario in terms of the number of users and their time frames has been defined for a whole year. The number of air exchanges used in the calculation is the one determined by a Blower-Door test of the building. The data used to determine the energy performance of envelope elements and building services are those of the manufacturers' performance declarations.

The objective of the life cycle assessment is to determine the environmental impact of the analysed educational building by CO_2 emissions in the implementation and usage phase. The defined life cycle for the analysed building consists of the production and installation of the actual quantities of building materials and energy consumption calculated over 50 years of use, based on maintenance and replacement scenarios. The processes taken into account for determining the impact of the implementation stage include structural, partitioning and closing materials, finishing and also their transport on site.

3. Energy efficient educational building - a case study

3.1. *General presentation*

The four storey building is located in the central area of the town of Salonta, Bihor county, in a predominantly residential area with related functions.

Regarding the ground floor, the public catering function is ensured by a dining room with a capacity of 192 people and a kitchen with the related functional spaces. The ground floor also provides space for a school library and a reading room. Of the 15 classrooms located on the first two floors, 6 are configured with specific facilities for thematic laboratories, which in turn are provided with annexes for storing teaching materials. Auxiliary rooms are also provided, such as: administration, secretary office, accounting, teacher room and psychological office. The third floor is dedicated to the boarding school which consists of 10 apartment type accommodation spaces. Each space consists of two rooms with three beds, a hall and common bathrooms. The accommodation capacity of the boarding school is 62 places. In addition, there are spaces for socializing, office-kitchen, supervisor room and medical office.

The thermal insulation used is made of extruded polystyrene at the foundation and the ground slab level, of rigid mineral wool for the exterior walls and lower exterior floors, and of semi-rigid mineral wool for the floor under the attic. To ensure the necessary utilities for the main building, the technical spaces were arranged in a neighboring independent building. The utilities provided for the building include: heating and cooling, mechanical ventilation with heat recovery, domestic hot and cold water, lighting and power supply of appliances.

Figure 1 – Overview of the building

3.2.Design concept

In the design stage, use of the configuration and detailing principles of the passive house standard and nearly zero energy building standard was ordered. To facilitate the verification of the energy behavior, a monitoring system of the energy balance and the interior comfort defining parameters has been designed and implemented.

The configuration principles that were used in the design of the building are:

- Compact volumetric configuration
- Use of high thermal resistance envelope elements
- Thermal bridge free envelope design
- Airtightness of thermal envelope
- Use of orientation to maximize solar gains
- Use of an efficient heating and cooling source
- Efficient distribution of heating and cooling
- Fresh air supply by mechanical ventilation systems with heat recovery

The non-structural surrounding closure of the building was made of AAC masonry. The thermal insulation of these elements is made of 150 mm thick rigid mineral wool. A 200 mm thick extruded polystyrene thermal insulation layer was laid on the ground slab. Reduction of heat loss and thermal bridge limitation under the perimeter ground concrete beams is obtained by designing a 120 mm thick thermal insulation layer of expanded polystyrene at a height of 0.80 m, at the external side of the perimeter foundations. The attic floor consists of a 130 mm thick reinforced concrete slab and a 250 mm layer of thermal insulation made of semi-rigid mineral wool. The thermal insulation of the lower exterior floor was made with 250 mm thick rigid mineral wool, ensuring continuity around the structural beams that represent geometric prominences of the reinforced concrete slab.

The predominant fraction of the exterior windows and doors was made of PVC frames of the Salamander bluEvolution92 brand. The windows are assembled on the outside of the closing walls' thickness using metal clamps and 100 mm wide sealing tape, on the inside and on the outside. The glazing used for the PVC windows is 52 mm thick with triple glazing (LE4/20Ar/4Fl/20Ar/LE4).

The thermal agent for heating, cooling and domestic hot water is made with two integrated reversible heat pump systems, of the Dimplex SI 75TER+ brand. The two heat pumps have an installed power of 75 kW each and are of different types: water-water (2 extraction boreholes and 2 injection boreholes at 110m depth) and ground-water (10 vertical boreholes at 110m deep). Domestic hot water is prepared with an Elbi BF-2-3000 storage heat exchanger with a volume of 3000 L, thermally insulated with 50 mm thick polyurethane foam. The types of thermal agent distribution elements in the rooms are: vertical floor-mounted fan coil units, ceiling-mounted fan coil units, and steel radiators for the bathrooms of the accommodation unit. The working temperature of all indoor thermal distribution elements is 45/35°C for heating and 10/15°C for cooling.

Figure 2 – Heat pumps and boreholes distributor

The fresh air supply of the building is ensured with the help of mechanical ventilation systems with heat recovery. Thus, the building is equipped with a total of six independent systems, namely in: library, dining room, kitchen and one for each floor. The air treatment plants have a circulating air flow capacity of 1000 m^3/h for the library and 4000 m^3/h for the resst. Their heat recovery efficiency is 68%. The use automation of the ventilation systems depend on the level of CO_2 detected by the sensors on the main suction ducts prior to entering the air treatment plant.

Before elaborating the technical project, a preliminary comparative study of the overall costs of the building in two constructive variants was drawn up: traditional and energy efficient.

Both the initial implementation costs and the usage costs were taken into account for assessing global costs. The comparative study was carried out with the financial data of 2014 in which the value of VAT was 24%. Furthermore, a discount rate of 2%, a devaluation rate of 3% and a RON/EUR exchange rate of 4.45 were taken into account. The results of the evaluation of the initial cost of the building in the energy efficient version was 565 EURO + VAT/m^2, and 510 EURO + VAT/m^2 for the traditional version. The cost difference between the two options was only 10%. Maintenance costs consist of the price of energy consumption for heating, cooling, domestic hot water, mechanical ventilation and lighting. For the traditional building a total specific consumption of 250 kWh/m^2/year was considered. For the energy efficient building a consumption of 45 kWh/m^2/year was taken into account. The energy prices considered are those related to the national average values for the second half of 2014, namely: for electricity 0.453 RON + VAT/kWh, for natural gas 0.112 RON + VAT/kWh. The difference in higher initial costs of about 10% of the energy efficient building determined by the preliminary assessment of the two building options is reimbursed over a period of 8 years, by the significantly lower costs of energy consumption.

4. Evaluation of the energy performance of the building

4.1. Heating energy consumption

The total specific electricity consumption of the building heating system of 17.85 kWh/m^2year falls into energy class A, and slightly exceeds the maximum limit allowed according to the Passive House Standard of 15 kWh/m^2year. The primary energy consumption of the heating system, calculated by multiplying with the conversion factor of electricity into primary energy ($f_p = 2.62$) is 46.77 kWh/m^2year and falls within the maximum limits allowed for educational buildings according to the national methodology (123 kWh /m^2year), and falls into the energy class A+ according to the proposed amendment to the calculation methodology (61 kWh/m^2year).

4.2. Hot water energy consumption

The total specific electricity consumption for the domestic hot water of the building of 13.12 kWh/m^2year falls into energy class A. The primary energy consumption for the domestic hot water system, calculated by multiplying by the conversion factor of electricity into primary energy ($f_p = 2.62$), is 34.37 kWh/m^2year and falls into energy class G according to the proposed amendment to the calculation methodology (19 kWh/m^2year). The reason for the unfavourable energy class framing, is the fact that the classification of domestic hot water consumption in energy classes of educational buildings takes into account types of buildings that usually do not contain accommodation units and kitchen for dining.

4.3. Cooling energy consumption

The total specific electricity consumption of the building cooling installation of 4.35 kWh/m^2year falls into energy class A. The primary energy consumption of the cooling system, calculated by multiplying by the conversion factor of electricity into primary energy ($f_p = 2.62$), is 11.40 kWh/m^2year and falls into energy class B according to the proposed amendment to the calculation methodology (9 ... 13 kWh / m^2year).

4.4. *Mechanical ventilation energy consumption*

The total specific electricity consumption of the mechanical ventilation of the building of 9.07 kWh/m^{2}year falls into energy class C. The inclusion in a lower energy class of the ventilation system is not a deficit as long as the total energy consumption of the building does not exceed the maximum values allowed for total energy consumption class A (150 kWh/m^{2}year). The primary energy consumption of the mechanical ventilation system, determined by multiplying by the conversion factor of electricity into primary energy ($f_p = 2.62$), is 23.76 kWh/m^{2}year and falls into energy class C according to the proposed amendment to the calculation methodology (20 ... 29 kWh/m^{2}year).

4.5. *Lighting energy consumption*

The total specific electricity consumption of the interior lighting of the building of 3.61 kWh/m^{2}year falls into energy class A. The primary energy consumption of the lighting system, determined by multiplying by the conversion factor of electricity into primary energy (f_p = 2.62), is 9.45 kWh/m^{2}year and falls into the energy class A+ according to the proposed amendment to the calculation methodology (10 kWh/m^{2}year).

4.6. *Total energy consumption*

The specific electricity consumption of the building of 48.02 kWh/m^{2}year falls into energy class A. The predominant fraction of the building consumption is represented by the heating system (37%) and energy consumption to provide domestic hot water (27%). The highest total monthly consumption is in December and January due to heating energy demands. July and August have the lowest consumptions due to the summer vacation of the school year, in which educational spaces are not used. In these two months only the third floor (accommodation unit) of the building is used.

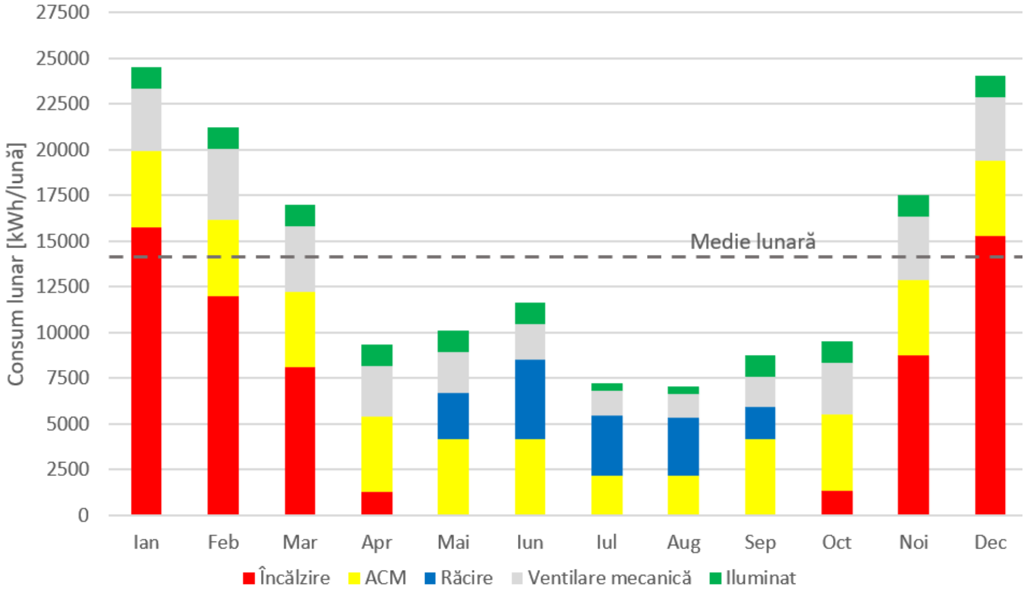

Figure 3 – Monthly distribution of total energy consumption

4.7. *Primary energy and CO_2 emissions*

The resulting total specific primary energy consumption of 125.81 kWh/m^{2}year slightly exceeds the maximum allowed limit for educational buildings according to the Classic Standard Passive House requirement of 120 kWh/m^{2}year, and it falls into energy class A according to the proposed amendment of the calculation methodology (90 ... 127 kWh/m^{2}year). For new classifications of Passive Houses the primary renewable energy consumption of 81.63 kWh/m^{2}year slightly exceeds the maximum allowed limit for typical educational buildings, according to the requirement of PHI Low Energy Building of 75 kWh/m^{2}year. For the classification of nearly zero energy buildings (nZEB), according to the proposed amendment of the calculation methodology (115 kWh/m^{2}year), the primary energy consumption slightly exceeds the maximum allowed limit for educational buildings in climate zone II.

The resulting CO_2 emissions of 37.62 kg CO_2/m^2year slightly exceed the maximum allowed limit for educational buildings and climate zone II for the classification of nearly zero energy buildings, according to the proposed amendment of the calculation methodology (30 kg CO_2/m^2year).

The primary energy consumption and CO_2 emissions of the educational building designed and implemented with energy efficient solutions are lower than those of the new or existing reference non-residential buildings that are made with traditional technical solutions. For a building of the size of the analysed construction, the amount of CO_2 emissions avoided by applying the technical solutions used in the educational building, compared to the results of the reference buildings, varies between 231 tons CO_2/year and 274 tons CO_2/year.

5. Monitoring system

5.1. The monitoring concept

The main purpose of implementing a monitoring system is to collect real-time data on the parameters that define the energy performance and interior comfort of the building. The system includes a network of measuring instruments and sensors that are connected to data acquisition stations. The monitoring infrastructure installed in the building transmits the collected information to a dedicated server using a building communication system via Wi-Fi.

The monitoring system consists of: type DS18B20 and NTC 20k digital thermometer temperature sensors, analogue flow meters with pulse output, single-phase digital electricity meters and gas meters. The connection of the sensors was made with JB-Y(St)Y cables of 2x2x0.8 mm and the route to the storage units was handled specifically as a low current electrical installations, using boxes and connection clamps.

Data collection is done by three data-logger units, two of which are located on the ground floor of the main building and one in the independent utilities building. Sensor readings are set to be recorded every 30 minutes. In total, the monitoring system consists of over 660 sensors and measuring meters, 94 connection boxes and 5 km of cable.

5.2. Monitoring of envelope elements parameters

The monitoring strategy consists in the installation of measuring positions in all opaque envelope elements so that they can provide real-time details of their heat transfer behaviour. Each envelope element is provided with measuring positions of the monitoring system to determine the temperature distribution in their thickness, at relevant points. All areas with thermal bridge reduction constructive solutions are provided with measuring positions of the monitoring system to verify compliance with the calculation assumptions. The sensor locations below the level of the systematized terrain aims to monitor the temperatures of the natural ground, under the footprint of the building and outside of it, as well as measuring the effect of the vertical thermal insulation mounted on the outer perimeter of the continuous foundations.

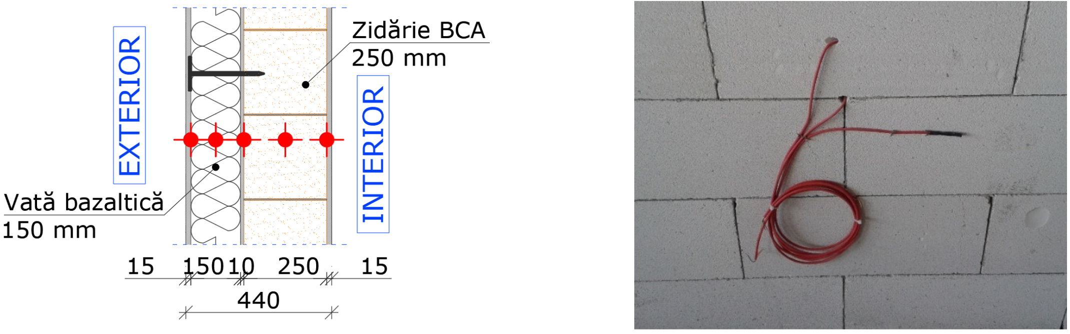

Figure 4 – Exterior wall temperature sensors

5.3. Monitoring the operating building services parameters

The components that monitor the building services have been established in such a way that provides both an overview and a detailed approach of their parameters. The elements that make up the complete route of the targeted system are those that determine the main energy consumption: central heating, thermal agent source, indoor thermal elements and the ventilation systems. The thermal system measurement concept includes temperature sensors and analogue flow meters with flow pulse output. The used temperature sensors are mainly DS18B20 digital thermometers, except for those mounted on the depth of the vertical boreholes which are of type NTC 20k.

Monitoring the parameters that define the performance of ventilation systems involves measuring temperatures at the relevant points of the entire air route, from outside to the rooms. The installation of the temperature sensors inside the ventilation ducts was done with connectors specific to electrical cable sealing systems. The standard equipment of the air treatment plant includes CO_2 sensors that are part of the automation and operation control system, according to the set parameters. These measuring instruments are integrated into the monitoring system by automatically recording readings using the remote control option of the device setup interface.

5.4.Monitoring of indoor climate parameters

The actual indoor climate conditions are necessary to complete the monitoring data in order to verify the compliance of the building to the calculation assumptions at the design stage. The indoor climate parameters set out in the monitoring system currently include temperature, humidity and carbon dioxide (CO_2). The strategy for monitoring this category of parameters consists of provisioning of a temperature, humidity and CO_2 sensor package in multiple areas of the building. The installation areas were chosen so that the parameters related to each function could be monitored according to the different conditions of use.

5.5.Metering energy consumption

The energy consumption of the building is monitored and metered in real time using seven electricity meters and two natural gas meters. The metering strategy consists of providing single-phase digital meters to measure all electricity consumption on each level, but also the technological consumption of the kitchen and the independent utilities building. The metering of the monthly electricity and gas consumption taken into account is for a period of two years, between March 2018 and February 2020.

The total metered values of the specific energy consumption of the building, including the technological equipment, is 29.75 kWh/m^2/year. During the metered period, the real usage conditions of the building include a low occupancy rate of the boarding school on the third floor. Taking into account the metered values without the technological equipment, the value of the specific energy consumption of the building is 23.81 kWh/ m^2/year. The value of the specific final energy consumptions calculated using the calculation methodology (48.02 kWh/m^2/year) are twice higher than the metered value of the building (23.81 kWh/m^2/year).

Regarding the heating season, the main causes of the magnitude of the difference between the metered and calculated values are the differences between the outdoor temperatures during the metered period and the monthly averages taken into account, and the use of the building in a different actual occupancy and heating regime than was assumed during calculation. Part of the monthly differences are due to the low occupancy of the third floor, which was calculated to be an important component of total energy consumption.

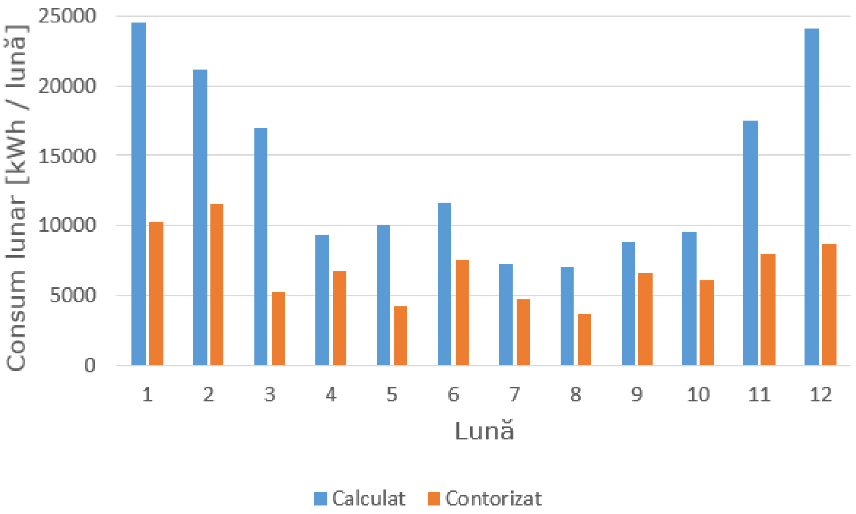

Figure 5 – Calculated and metered monthly electric energy consumption comparison

5.6. Thermography

The aim was the additional qualitative verification of the implementation works of the thermal envelope components, and also of their energetic behaviour, by thermography [12]. The procedure was performed on 16.01.2018 using a Flir InfraCam B thermograph.

The temperature differences between the external surfaces of the existing neighbouring building and the analysed building of 8-9°C show the major qualitative difference between them, favouring the energy efficient building. Furthermore, the temperature values of the external surfaces of the educational building being close to the outside environmental conditions, proves that the thermal envelope operates properly.

The detailed thermal images made from outside and inside show thermal bridges on the perimeter of the windows installed in the masonry wall. This is due to the chosen constructive solutions and to the local deficiencies in solving the installation details of the sealing tapes. Temperatures on the interior surfaces of areas with deficiencies are lower than for envelope elements that are properly installed, and the local effect is manifested by a pronounced heat flow and decreased interior comfort.

5.7. Blower-door test

The verification of the building airtightness and of the quality of the window installation was performed using a Blower-Door Test [13]. The test aims at the quantitative and qualitative determination of the airtightness of the thermal envelope by a differential pressure measurement and determines the number of air changes per hour (n_{50}) at a pressure difference of 50 Pa. The test was performed with the following equipment: Blower-Door fan with a capacity of 8000 m^3/h, compact thermal anemometer with flow probe and a smoke generator. After performing the test, the results were $n_{50} = 0.4760\ h^{-1}$ and $n_{-50} = 0.4935\ h^{-1}$, values that fall within the limits of $n_{50} < 0.60\ h^{-1}$. The fulfilment of the sealing condition was due to the proper use and installation of the sealing tapes on the exterior windows, the sealing of the frame sash of the windows provided with movable meshes, and by limiting perforation of the thermal envelope by the building services components.

5.8. Quality control

To ensure the implementation of the project according to the concept and design details that aimed to obtain not only an energy efficient building, but also one with high quality standards in all of its components, the design and management team undertook the technical support and consultation of all stakeholders. After the final reception, the administrative staff was trained for the maintenance of the building, to ensure a good understanding of the operation of their systems and for the adjustment of its parameters according to various usage scenarios of the building. With regard to the use of the building, an internal regulation has been drawn up that lays out the necessary compliance measures for operating the building under normal parameters.

5.9.Measurements

The purpose of measuring the temperatures in real time is the numerical modelling of the thermal flux of the readings, the calibration of the numerical calculation model and determining of actual energy losses. One of the main reasons for implementing the monitoring system is to provide data through which calibrated models can be generated based on actual consumption. To date, due to the very large amount of data, only partial data processing for the implementation period has been carried out. The recorded temperature values demonstrate that the details proposed for thermal insulation are appropriate.

6. Life cycle assessment

The environmental impact of the analysed educational building was assessed by determining the CO_2 emissions during the building life cycle, and its implementation and usage stages [14]. The defined life cycle for the analysed building consists of the production and commissioning of the actual quantities of building materials, and the calculated energy consumption during 50 years of use.

6.1.Input data

To determine the effects of technical solutions for energy efficiency in educational buildings, the analysed construction is compared with two types of reference buildings. The reference buildings differ from the building analysed mainly by the use of natural gas condensing plants to the detriment of heat pumps, and by the thermal performance of the enveloping elements, which are equal to the minimum values required by the national calculation methodology.

6.2.Carbon footprint of the implementation stage

The processes taken into account for determining the impact of the implementation stage include the structural, partitioning and closing materials, finishing, and also their transport on site [15]. The components of the building services are not taken into account. Determining the footprint of the three types of buildings was achieved using the calculation program developed by the Environment Agency UK [16], the carbon footprint databases of the building materials of the University of Bath and the British Cement Association. The carbon footprint of the analysed building is 4% higher than that of the other two types of reference buildings. The differences are due to the higher amounts of thermal insulation and glass used for the analysed building.

6.3.Evolution of final and primary energy consumption

The final energy consumption of the three types of buildings analysed was determined based on replacement scenarios of the main components of the building services. The calculation principle involves reporting percentage of interventions to specific consumptions in the first year of use. Based on the replacement scenario with components of superior technical performance and the effects of increasing the average annual temperatures, the final energy consumption of the three building variants decrease in time.

The evolution of primary energy consumption is determined by considering the previously determined final energy consumption and variable factors of conversion into primary energy of electricity ($f_{p,el}$) and natural gas ($f_{p,gas}$). The time variation of $f_{p,el}$ is based on the result of the study conducted by the Fraunhofer Institute in 2016. The annual percentage decrease of the $f_{p,el}$ value taken into account was determined by the average annual differences of the four calculation methods between 2020 and 2030. The time variation of $f_{p,gas}$ was determined by an annual increase of 0.25%. Based on the evolution scenario of $f_{p,el}$ and $f_{p,gas}$, the primary energy consumptions of the three building variants are descending in the considered period.

At the end of the analysed period, the difference of primary energy consumption between the analysed building and the reference buildings was 186 kWh / m^2year, or 277%. In terms of global consumption, after 50 years of use, the primary energy saving of the analysed building compared to the reference buildings was 33.4 GWh.

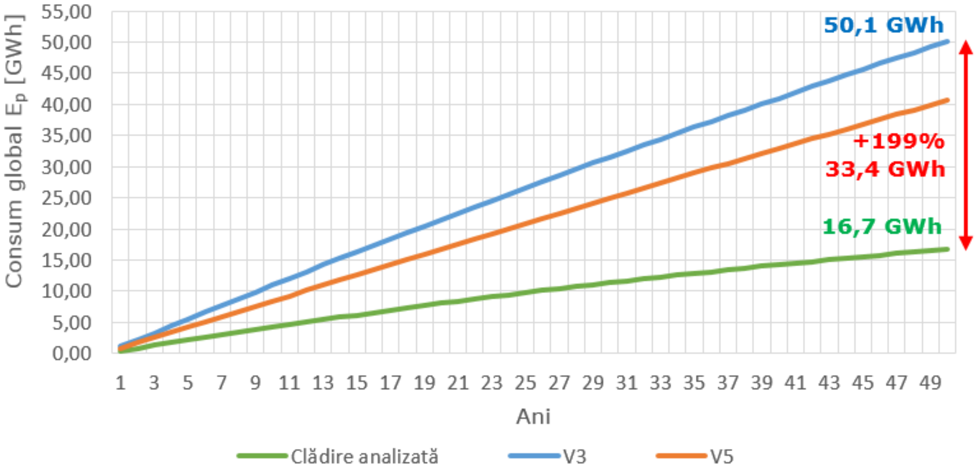

Figure 6 – Global primary energy consumptions

6.4.*Evolution of CO_2 emissions*

To determine the evolution of specific emissions of CO_2, the emission factors for electricity ($f_{CO2, el}$ = 0.299) and natural gas ($f_{CO2, gas}$ = 0.205) were taken into account according to the values provided by the national calculation methodology. At the end of the analysed period, the difference in CO_2 emissions between the analysed building and the reference buildings was 38.3 kg CO_2 / m^2year. In terms of global CO_2 emissions, after 50 years of use, the amount of avoided emission of the analysed building compared to the reference buildings is 6966 tons of CO_2.

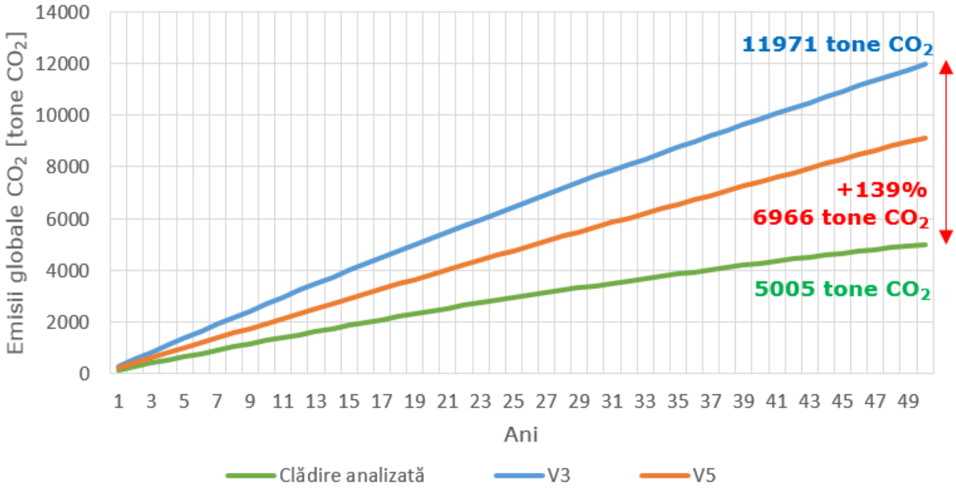

Figure 7 – Global CO_2 emissions

6.5.*Global cost*

Determining the global costs of the three types of buildings aims to analyse the financial feasibility of technical energy efficiency solutions over 50 years of use.

The components of the global cost that have been taken into account include:

- Initial investment costs
- Annual maintenance costs (equivalent to final energy consumption for heating, domestic how water, cooling, mechanical ventilation and lighting)
- Annual maintenance costs
- Annual replacement costs

The considered gross price of the analysed building is in line with the real one, and is the basis on which it was created. The evolution of the unit price of electricity is based on the average annual increase in Romania, namely 0.85% [5]. The evolution of the unit price of natural gas is based on the average annual increase in EU Member States and the World Bank's estimate [6] of the increase of the unit price in Europe between 2020 and 2030, of 2%. The gross unit prices of electricity (0.6494 RON/kWh) and natural gas (0.1610 RON/kWh) considered in the calculation are those from Eurostat [5] statistics for the second half of 2019.

At the end of the analysed period of 50 years, the difference in the global cost between the analysed building and the reference buildings is 1,363,000 €, or 27%. The amortization period of additional investments of 10% for the implementation of energy efficiency solutions of the analysed building is 11 years.

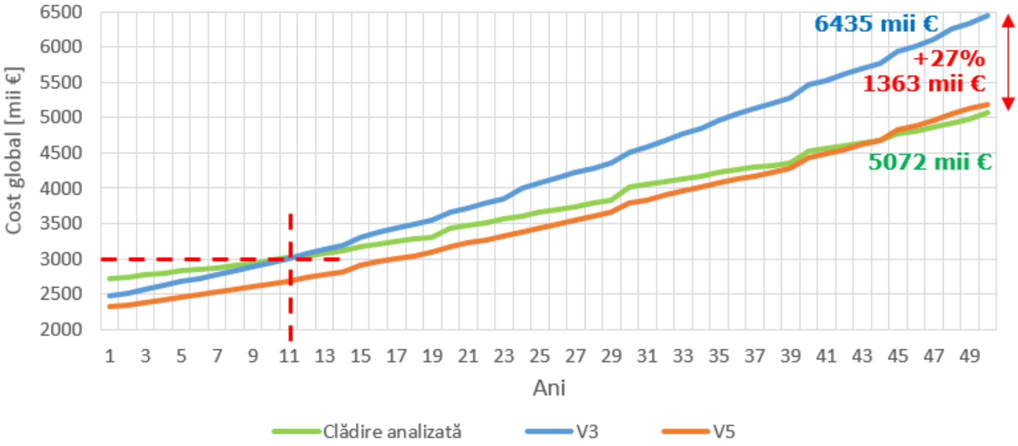

Figure 8 – Global cost evolution

7. Conclusions

7.1.Research Conclusions

The main conclusions of the research activity and the interpretation of the results are:

- The evolution of research and studies in the field of energy efficiency of buildings has shown that improving the energy performance of buildings can be an appropriate tool to meet the strategic objectives of reducing the impact on the environment by 2050.
- The conversion factor of electricity into primary energy is an essential parameter in the global energy context.
- The ratio between the unit price of electricity and natural gas is a decisive factor in choosing the energy source of buildings. In the first half of 2020, the ratio was 2.83 for the EU average and 4.39 for Romania.
- The proposal to change the national calculation methodology brings improvements in terms of calculation procedures, available data, transparency and technical requirements on the energy performance of buildings. It is proposed to create simplified methods of classifying the energy consumption of buildings and to draw up energy certificates.
- The energy performance and interior comfort of buildings that comply with the principles and technical requirements of Passive House and nZEB are significantly better than those of buildings made with classic and traditional methods.
- Monitoring systems of the performance and energy consumption of buildings can be a suitable tool for calibrating numerical calculation models.
- The life cycle assessment method can be used to compare buildings made with different technical solutions, but also to provide assistance to decision makers on long-term building performance.
- The total final energy consumption of the building, calculated on the basis of the national calculation methodology, is 48.02 kWh/m^{2}year, of which 17.86 kWh/m^{2}year for heating, 13.13 kWh/m^{2}year for domestic hot water preparation, 4.35 kWh/m^{2}year for cooling, 9.07 kWh/m^{2}year for mechanical ventilation, 3.61 kWh/m^{2}year for lighting.

- The total primary energy consumption of the building, calculated based on the national calculation methodology, is 125.81 kWh/m^{2}year. The small differences between the energy performance of the building and the technical framing requirements presented can be eliminated by equipping it with photovoltaic panels.
- The differences between the analysed building and the building made with traditional technical solutions and energy sources based on natural gas, are: +328% for final energy, +153% for primary energy and +109% for CO_2 emissions.
- The implemented monitoring system is a source of real time data, through which the energy behavior of the building can be analysed in detail.
- The value of the specific final energy consumption calculated based on the calculation methodology (48.02 kWh/m^{2}year) are twice higher than the metered value of the building (23.81 kWh/m^{2}year). This is due to the differences between the outdoor temperatures during the metered period and the monthly average values taken into account during modelling, and the actual use of the building in a different occupancy and heating regime than the calculation assumptions.
- Specialized consulting, technical assistance and quality control throughout the implementation process, tracking behavior over time and training users were essential activities to achieve the projected energy performance.
- The impact on the environment through the carbon footprint and CO_2 emissions of the analysed building for 50 years of use are significantly lower than those of buildings made with traditional technical solutions.
- At the end of the analysed period of 50 years, the difference in the global cost between the analysed building and the building made with traditional technical solutions and natural gas sources (V3) is 1,363,000 €, or 27%. The amortization period of additional investments of 10% for the implementation of the technical solutions of energy efficiency of the analysed building is 11 years.
- The construction and operation of the educational building can be an example of good practice for the implementation of similar investments.

7.2. Personal contributions

- Elaboration of a preliminary study for energy efficient construction solutions.
- Coordinating the design team, structural detailing and dimensioning, establishing innovative energy efficient envelope constructive solutions, project management, coordinating the technical assistance team in the implementation stage, training and consulting the building administrator in the usage stage.
- Analysis and study of a considerable number of scientific papers, research activities.
- Creating a research infrastructure by implementing the monitoring system, unique in complexity.
- Organization and design of Blower-Door airtightness test and thermography.
- Calculation of the energy performance of the building by complex methods using a high volume of data and its calibration with the characteristics of the implemented materials and details.
- Processing, analysis and interpretation of energy consumption recorded in the usage phase. Comparison of real energy consumption with calculated theoretical values and justification of the differences between the two values.
- Proposing changes to the calculation methodology: improving the method of assessing the energy consumption of non-residential buildings and with discontinuous occupancy based on actual measured values, changing the strategy for applying the calculation methodology according to the importance category of the respective building, depending on the purpose of obtaining the energy certificate.

7.3. Continuing the research activity

The following activities are proposed to continue the research:

- Completing the monitoring system with missing elements, processing, analysing and interpreting the monitored data for a period of at least 10 years.
- Calibration of the numerical calculation model with the recorded data and performing a calculation of energy performance in dynamic regime.
- Equipping the building with a photovoltaic panels, additional automation of heating and ventilation systems, external shading systems and with additional electricity consumption meters.
- Monitoring the behavior and health of users, respectively the CO_2 room levels.
- Implementation of monitoring systems for other buildings with discontinuous occupation, and also in other climatic zones.
- Construction of a monitoring database with automated processing, evaluation and interpretation, to be used for calibrating calculation methodologies and validating optimal technical solutions for energy efficiency of buildings.

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