STUDY ON BUILDING ENERGY EFFICIENCY USING NUMERICAL SIMULATIONS AND IN SITU MEASUREMENTS

PhD thesis – Summary

To obtain the scientific title of Doctor at
Politehnica University Timişoara
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author eng. Cristina-Mariana TĂNASĂ
scientific adviser Prof.univ.dr.ing. Valeriu Augustin STOIAN

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Abstract

The building sector is the largest energy consumer, accounting for more than a third of total global energy consumption and is implicitly a major source of carbon dioxide emissions. This sector has been identified as having major energy efficiency potential and is a key actor towards climate change mitigation. At the European Union level, the concept of nearly zero energy building was introduced as a standard to be achieved in buildings. In this context, studies on energy efficiency through measurements and numerical simulations can lead to the validation and improvement of technical solutions towards the achievement of nearly zero-energy buildings. The Recast on the Energy Performance of Buildings Directive defines the optimal cost methodology, whereby energy efficiency solutions are correlated with the economic aspects in order to identify the lowest global cost. This PhD thesis presents studies based on the monitoring of an energy-efficient pilot building. The results of the monitoring process have determined the actual energy consumption of the building by categories of consumers and the analysis of indoor climate parameters (temperature, relative humidity, CO_2 concentration). Some of the data collected by the monitoring system has been processed and implemented in a building energy model to achieve a hourly dynamic simulation that reflects the actual building and operation conditions (temperature, lighting, climatic data, etc.). The results of the numerical simulations show very small differences compared to measurements. Thus, based on a calibrated simulation, parametric studies were conducted to optimize energy consumption and indoor temperature. The last part of the thesis is based on the application of the cost optimal methodology, for which 19 packages of measures for building envelope and technical systems, including renewable energy generation systems, have been proposed. The latter study aims at identifying those solutions that lead to the achievement of nearly zero energy buildings and, at the same time, identifying the optimal cost solutions.

Thesis chapters summary

1. Introduction

This presents the frame of reference for the thesis theme followed by the research motivation and thesis objectives.

1.1. General aspects related to energy consumption

Not only in the EU but worldwide, the building sector has the largest share of energy consumption from the total energy consumption (almost 40%) and therefore is responsible for a high amount of greenhouse gas emissions. Improving the energy efficiency of buildings is crucial in order to achieve the EU objective of reducing the greenhouse gas emission by 80-

95% until 2050, compared to 1990 [1]. Directive 2010/31/EC introduces the concept of ‚nearly zero energy building' (nZEB) that have a nearly zero primary energy consumption from fossil fuels and very low level of CO_2 emissions. The recast on the Energy Performance of Buildings Directive (EPBD) defines the nZEB as "a building that has a very high energy performance [...]. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby" [2].

1.2. Research motivation and objectives

The main challenge in achieving the targets set by the Energy Performance of buildings Directive consists in providing highly energy efficient solutions that are at the same time cost-effective. In order to provide reliable and efficient solutions for building owners, experimental and theoretical studies that investigate the response of such buildings are necessary.

The main objectives of this thesis can be summarised in the following:

- Processing and analysis of the monitoring data of the investigated energy efficient building.
- Implement measured data in the building energy model in order to achieve a calibrated simulation.
- Validate the theoretical results from the numerical simulations against measured data in terms of energy consumption and interior air temperature.
- Investigate changes in the building operation parameters that might increase or decrease the energy consumption of the buildings, through numerical simulations.
- Investigate several energy efficiency scenario applied to the case study building with the aim of identifying those solutions that lead to the achievement of nZEBs and, at the same time, identifying the optimal cost solutions.

1.3. Overview of the thesis

This subchapter summarizes the thesis content, presenting briefly the content of each chapter. This thesis is structured on seven chapters from 1 to 7 and four appendices A, B, C and D. The content of the seven chapters and four appendices has a total number of 195 pages.

2. Research method

This chapter defines the main concepts applied in the research from the perspective of the related existing studies and research.

2.1. Energy efficient buildings concepts

The research in this thesis refers to several energy efficient buildings concepts. The passive house concept is nowadays probably the best known energy efficient building concept, with numerous implementations worldwide. Passive house principles aim at reducing to a minimum the heat losses and optimize the internal heat gains so that the heating energy demand does not exceed 15 kWh/m^2y. While the passive house standard offers detailed design principles, the nZEB is only defined through numerical indicators for primary energy from non-renewable energy and renewable energy ratio and no guidelines on how to achieve this standard is provided. Studies performed by the Passive House Institute claim that the passive house concept, which is nowadays a well-known building standard, can be a basis in achieving the nZEB target [4].

2.2. Primary energy

The conversion of final energy of a building (electricity, natural gas, wood etc.) to primary energy is made by means of a primary energy factors, which indicates the amount of primary energy used to provide a unit of end use energy. The characterization of nZEB expressed in terms of primary energy, as required by the EPBD, is to be made with the use of two indicators: primary energy indicator and share of renewable energy from the total energy consumption. According to the technical definition of nZEB presented by Kurnitski [5], the primary energy indicator is calculated based on the sum of all imported and exported energy (calculated using national level primary energy factors) and useful floor area. The renewable energy share is determined based on total primary energy consumption. The total primary energy consumption is calculated based on all energy consumption of the building, including solar thermal, electricity from photovoltaic panels and/or wind, renewable energy from heat pumps etc.

2.3. *Methods in building energy modelling*

Currently, building energy modelling (BEM) is increasingly used throughout the life cycle of a building for commissioning, operation and optimization [6], [7]. Moreover, with the use of data from monitoring systems related to energy use, indoor environment parameters, internal heat gains, calibrated simulations can be performed. There are a lot of uncertainties and interacting variables that can affect the accuracy of the simulation results in a building energy model. The use of building energy performance simulation in the operational phase of a building can lead to the detection of potential failures and performance optimization, when comparing measured data with simulation results [8]. Currently there are several available energy simulation tools that have different levels of complexity and capabilities. The most common and widely used are Energy Plus [9] and TRNSYS [10]. In this thesis, EnergyPlus software tool was used which is a whole building energy modelling tool which performs calculations on an hourly basis.

2.4. *Building monitoring systems*

Implementing a monitoring system in a building represents a way of evaluating the real performances of a building, which is an important aspect to be considered when dealing with new technical solutions and high expected energy performance. By monitoring, the real energy consumption can be optimised and also offers necessary data for building performance analysis, energy model calibration and validation. Table 1 contains the relevant steps to be followed when dealing with building monitoring.

Table 1 - Relevant steps for building monitoring process [11]

Measurement and Verification Protocol	1. Building data collection 2. Monitoring boundaries 3. Metrics and relevant data 4. Frequency and duration of measurements 5. Suitable sensors and data acquisition system 6. Planning of the monitoring equipment and installation 7. Definition and implementation of data post-processing

2.5. *Energy efficiency and economic analysis*

Directive 2010/31/UE [2] introduces the "cost optimal" or "cost-effective" notions to be considered when developing nearly zero-energy buildings technical solutions. Cost-optimal level is defined as "the energy performance level which leads to the lowest cost during the estimated economic lifecycle. The cost is determined taking into account initial investment costs, maintenance and operating costs (including energy costs and savings, the category of building concerned, earnings from energy produced). The cost optimal methodology is defined in accordance to the EPBD recast and Delegated Regulation no. 244 [3].

3. Case study building

3.1. *General information*

The research in this thesis is based on a residential energy efficient building, which is in use and continuously monitored for several years now. The investigated building is part of duplex building, constructed near the city of Timisoara (Dumbravita), Romania. The premise of this project was to build a house following the passive house design principles and using materials and technologies specific to residential constructions in the area.

3.2. *Design concept*

The building was designed by the architectural studio SDAC from Timisoara and the design team was leaded by an architect that followed the passive house designer courses held at the Passive House Institute in Darmstadt. Therefore, special attention was paid to the architectural and structural details in order to obtain an efficient thermal envelope and strict control of the air exchange between the interior and exterior environments.

3.3. *Architecture, structural system and envelope*

From architectural perspective, the investigated building is a two floors building with a rectangular horizontal plan and prismatic volume. The structural system consists in concrete foundation blocks connected by foundation beams, structural masonry walls with reinforced concrete columns and belts and wooden beams floor. The envelope elements are highly insulated with polystyrene plates and mineral wool, leading to thermal transmittance values below 0.15 W/m^2K.

3.4. *Building systems*

The house has a complex system providing heating, ventilation, cooling and domestic hot water. The key components of the system are a heat recovery ventilation and an underground heat exchanger for fresh air input, air-to-water heat pump and a solar collector for domestic hot water. The house is equipped with a hot water boiler and a heating buffer for thermal energy storage. The heat is distributed throughout the rooms through convectors installed in the ceiling. The house is all electric, all the equipment use electrical energy from the grid.

3.5. *Building construction*

The construction of the house has been carefully managed to assure the quality of the thermal insulation system, avoiding any potential thermal bridge and ensuring the airtightness of the construction.

4. Building monitoring: registered data processing and analysis

This chapter presents the monitoring system of the case study building along with the monitoring data processing and analysis.

4.1. *Monitoring system*

The monitoring system is composed of a central unit and several ambient/energy meters and sensors. The structure and components of the monitoring system come from the categories of parameters that have been proposed to be monitored: indoor comfort and environmental conditions and indoor air quality, exterior environment parameters, energy consumption of the building, plant and equipment parameters. Each measurement component has a unique ID. The registered data is stored on a server and can be downloaded as Excel files for each month. The monitoring process is available online at http://www.sdac.ro/site/archives/796 .

4.2. *Monitoring data processing*

The monitoring process was initiated at the end of 2011. The system registers values at each minute and stores them on a server. The data files can be downloaded from the server as spreadsheets files for each month. Each monthly file contains approximately 44000 lines of values for each measuring component. The processing of the monitoring data was performed using Microsoft Excel tool. A set of data from 2015 was used in this research. The first step in processing the data consisted in detecting and eliminating errors and unusual peaks. Further, the data was processed to hourly, monthly and yearly values.

4.3. *Monitoring data analysis*

The monitoring results related to interior air temperature, air relative humidity, CO_2 concentration and energy consumption are presented in this section.

5. Building energy model simulation

5.1. *Description of the energy simulation tool EnergyPlus*

EnergyPlus is a whole building energy simulation software that is used to model energy consumption in buildings (heating, cooling, ventilation, lighting, hot water use) and process loads, on an hourly basis. The targeted audience of the software are design engineers or architects that want to size heating ventilation and cooling (HVAC) equipment, perform energy rehabilitation of buildings studies, optimize energy performance, perform parametric studies and investigate different building operation scenarios or different energy efficiency measures [13].

5.2. Development of the building energy model

This subchapter follows the process of creating the building energy model. The methodology is presented in Figure 1.

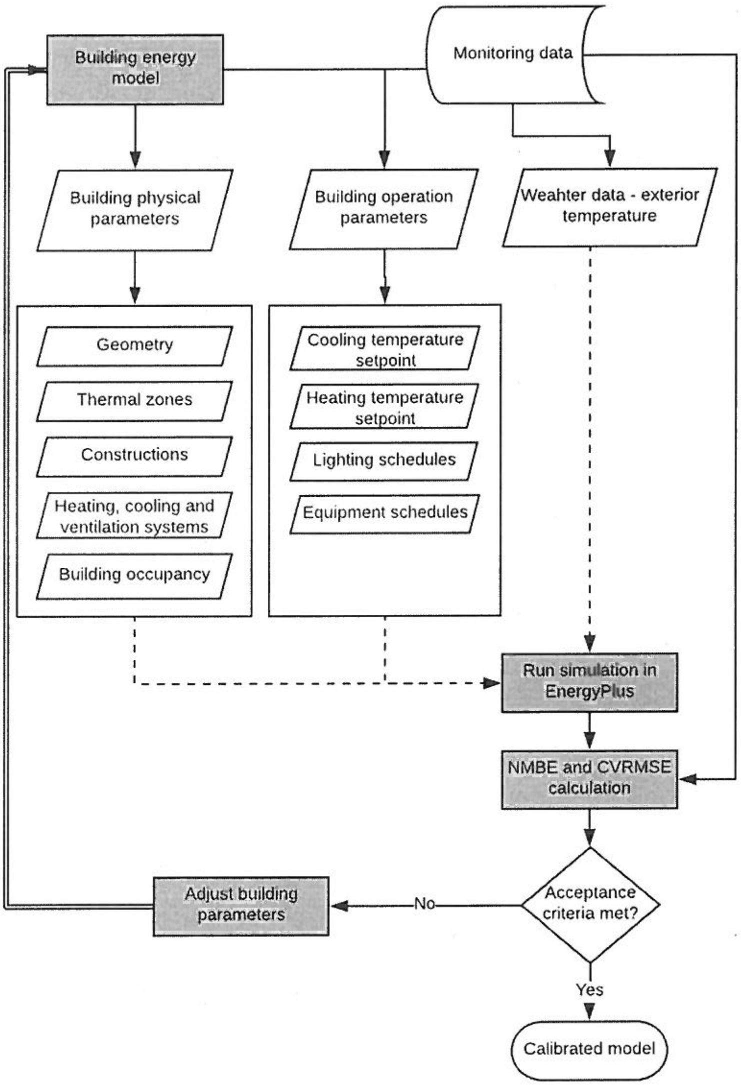


Figure 1 - Building energy modelling and calibration procedure

The aim was to develop a building energy model using real operation conditions and to calibrate the simulation. The building geometry was defined using as-built drawing of the building. Construction materials were defined according to as-built construction drawings as well. The building systems features were defined based on the technical sheets provided by the manufacturers of the equipment. The following measured parameters were used for the building energy model: hourly interior temperature for heating and cooling temperature set points schedules, hourly exterior temperature, measured infiltration rate, hourly lighting and electric equipment energy consumption for internal loads. A set of data from 2015 was used for the calibration. A custom weather data file was generated using hourly measured values for the exterior temperature, air relative humidity and wind speed. Also, the hourly measured temperature of the air after passing through the earth to air heat exchanger was defined as air node for the mechanical ventilation system. When the building energy model was complete and had all the information, the first simulation was ran. An error verification was carried out in order to validate the results of the simulation, in terms of normalized mean bias error (NMBE) and coefficient of variation of the root mean square error (CVRMSE).

5.3. *Building energy simulation results and comparison to measured data*

The total annual measured energy consumption of the building in 2015 was 5713.4 kWh and the building energy model predicted a value of 5776.7 kWh, resulting that the simulation over-predicted the total energy consumption of the building with 1.11%. The results presented in Table 2 shows that the NMBE and CVRMSE values for monthly data are within the acceptance limit recommended by ASHRAE Guideline [12].

Table 2 – NMBE and CVRMSE energy consumption values for the final building energy model

Category	NMBE*	CVRMSE**
Total energy consumption	-1.107 %	3.843 %
Heating, cooling, ventilation and domestic hot water	-1.376 %	5.054 %
Lighting	0.487 %	1.234 %
Interior equipment	-0.327 %	1.385 %

*NMBE acceptance limit ≤ ± 5% [12]

**CVRMSE acceptance limit ≤ +15% [12]

The accuracy of the building energy model in predicting air temperature was assessed as well. The overall NMBE and CVRMSE values calculated for hourly instances of time are -0.82%, respectively 5.72% and follow the calibration criteria to hourly values (±10%, 30%). Over the entire year, the measured indoor air temperatures are lower with and average value of 0.20ºC.

5.4. *Heating temperature set point and energy consumption*

For this case study, the impact of heating temperature set points on overall energy consumption was studied. Using the calibrated building energy model, 4 other simulation scenarios were performed using lower (-1°C and -2°C) and a higher temperature (+1°C and +2°C) set-points for heating. The energy consumption for heating can decrease with 8% and 17.3% for the lower set-points and can increase with 13.7% and 23.2% for the higher set-points. The results of this research emphasize the sensitivity of the overall energy consumption of a building to the heating temperature set-point.

5.5. *Simulation considering shading devices for windows*

The analysis of the interior air temperature during summer, both simulated and measured, shows that in several times the building faced overheating. Exterior blinds for windows were implemented in the building energy model. The proposed shading systems consist in exterior venetian blinds with horizontal slats. The most frequent values are below 27°C in case of the building with exterior shadings. For the other situation, the most frequent interior temperature values are above 26°C.

6. Towards nearly zero-energy buildings: cost-optimal analysis

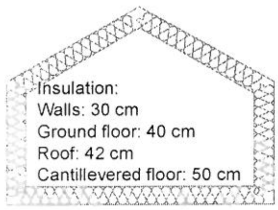
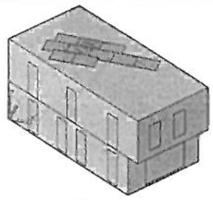
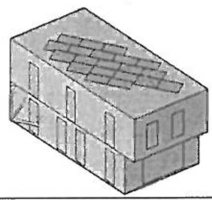
6.1. *Introduction*

In Romania, the maximum admissible primary energy from fossil fuels has been defined for different building categories, depending on the climatic zones of Romania. The building investigated in this thesis is located in the Romanian climatic zone II. For all new residential buildings located in climatic zone II the maximum admissible specific primary energy from conventional sources is 111 kWh/m^{2}year, in order to be considered nZEB [14]. Also it has been decided that the renewable energy must cover at least 10% of the total primary energy of a nZEB. This chapter investigates several energy efficiency scenarios applied to the case study building, aiming to achieve the nZEB target as well as determining cost-optimal solutions.

6.2. <u>Energy efficiency scenarios</u>

The proposed energy efficiency scenarios are either upgrades that can be implemented in the existing building or different other configurations of thermal envelope and technical systems, including on-site renewable energy production. In order to emphasize the energy and economic performance of the proposed solutions, the assessment is performed in comparison to a reference building, which has the same geometrical characteristics, volume and envelope elements areas as the real building, but complies with the minimum requirements in terms of energy efficiency. The scenarios proposed for envelope, technical systems and on site renewable energy production are listed in Table 3. The energy efficiency packages that will be applied to the case study building are defined as combinations between the measures proposed in Table 3. A supplementary measure that is not listed consists in shading systems (S). A total number of 19 energy efficiency packages were investigated, including the reference building and the real building. The packages name include: envelope scenario_technical system_shadings+renewables.

Table 3 – Proposed energy efficiency measures

<table>
<tr><th colspan="2">Envelope scenarios</th><th colspan="2">Technical systems scenarios</th><th colspan="2">Renewable energy scenarios</th></tr>
<tr><td>PH</td><td>
</td><td>I</td><td>– Air to water heat pump
– Solar collector
– Mechanical ventilation with heat recovery and earth to air heat exchanger</td><td>2.4 kW</td><td></td></tr>
<tr><td rowspan="2">EE</td><td rowspan="2">
</td><td rowspan="2">II</td><td rowspan="2">– Soil to water heat pump
– Solar collector
– Mechanical ventilation with heat recovery and earth to air heat exchanger</td><td>3.6 kW</td><td></td></tr>
<tr><td>4.8 kW</td><td></td></tr>
</table>

6.3. <u>Energy consumption evaluation</u>

The energy consumption evaluations of the energy efficiency packages earlier presented was performed using the dynamic building simulation software EnergyPlus. The construction of the models started from the already existing building energy model of the real building by modifying the features to match each of the energy efficiency packages. The primary energy consumption from non-renewable sources (also called net primary energy) is calculated for each package. The primary energy from non-renewable sources is calculated based on the delivered and exported energy, using primary energy conversion factors [3]. Thus, the primary energy from non-renewable sources is calculated as the difference between the primary energy corresponding to the energy imported from the grid and the primary energy corresponding to the energy exported to the grid.

6.4. <u>Economic analysis based on global cost</u>

The global cost calculation was conducted following the guidelines provided in Delegated

Regulation no. 244 [3] and standard EN 15459 [15]. A period of analysis of 30 years was used in this thesis. A discount rate of 3% was used, as it is the same rate used by the Romanian authorities in global cost and cost optimal calculations [16]. The global cost was calculated considering the following costs categories: initial investment, replacement costs, maintenance costs, energy costs, residual value.

6.5. Derivation of cost-optimal level of energy performance

Subsequently to the primary energy and global cost calculations of each of the proposed building packages, a graph is plotted to detect which are the cost optimal solution but also to see the economic and energy performance of each solution compared to the others. Thus, the graph in Figure 2 displays the specific primary energy and global cost values for each investigated energy efficiency package. On the graph is also plotted the specific primary energy requirement for residential nZEB in climate zone II, Romania.

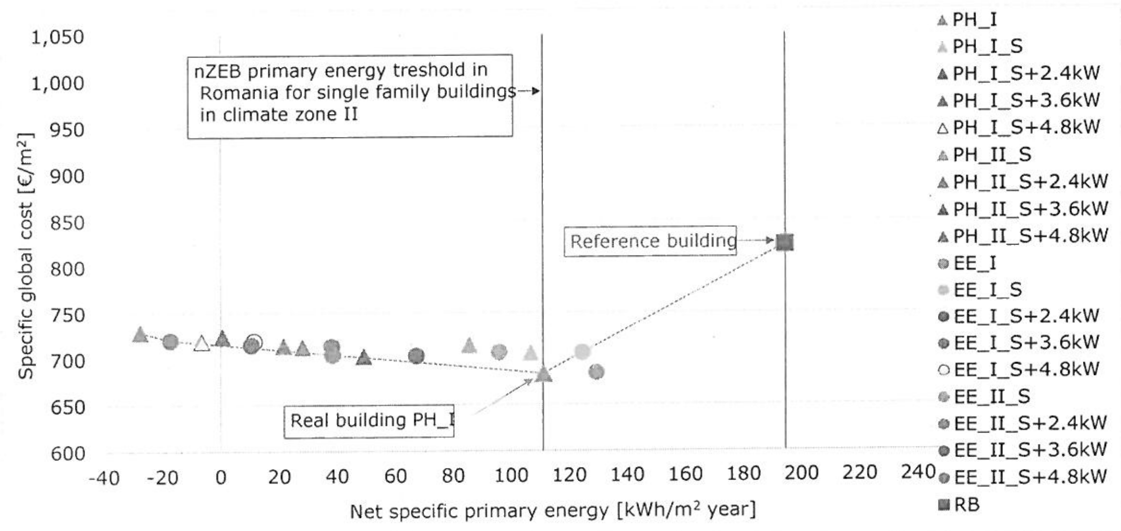


Figure 2 – Specific primary energy and global cost graph

6.6. Analysis of sensitivity to the discount rate values

A sensitivity analysis was performed for different discount rates, one higher (5%) and one lower (1%) than the base case. This analysis investigates the way in which the global cost is affected by the uncertainties which are included in the discount rate estimations. The results are plotted in Figure 3, comparatively to the base case situation (discount rate 3%). Buildings that have a low energy consumption are not so sensitive to the changes that financial market might encounter throughout the life-cycle.

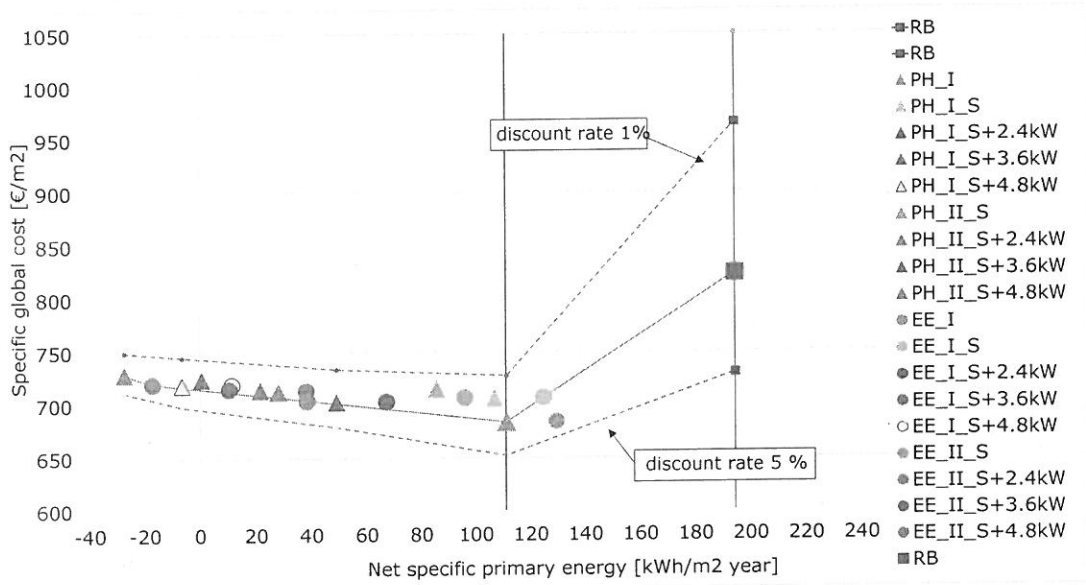


Figure 3 – Analysis of sensitivity to the discount rate

6.7.Analysis of sensitivity to the future development of energy prices

Another sensitivity analysis considers different energy price escalation rates, compared to the base case scenario (1.5% for electricity and 5% for natural gas). The results are plotted in the graph in Figure 4. As expected, the sensitivity analysis on the price development rate reveals that the energy efficiency packages with the lowest energy consumption are the least influenced by the future evolution of energy prices.

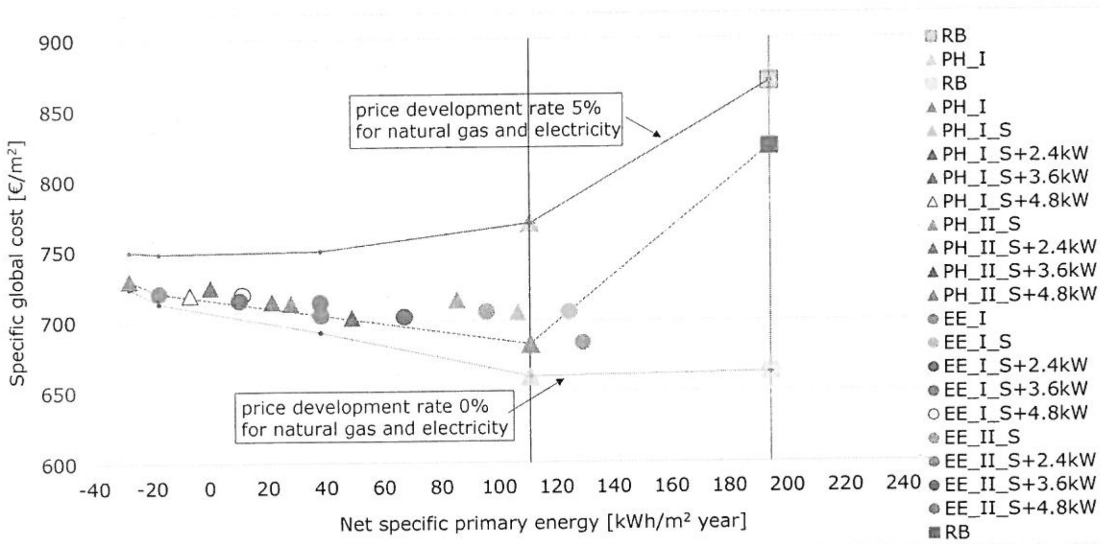


Figure.4 – Cost-optimal sensitivity analysis – energy price development rate

Another global cost analysis was performed considering that the surplus energy produced by the photovoltaic panels and exported to the national grid is not repaid. In this situation, the global cost increases for the energy efficiency packages that include photovoltaic panels, but still remains below the global cost of the reference building.

7. Conclusion

7.1.Conclusions of the research

Following the research and the analysis of the obtained results, the following main conclusions can be drawn:

- The existing studies and research related to energy consumption throughout the world reveal that the building sector has the highest potential of reducing the energy consumption from fossil fuels and the related greenhouse gas emissions, as it is the sector with the highest share on the total global energy consumption.
- Implementing a monitoring system in a building represents a way of optimizing the real energy consumption and also offers necessary data for building performance analysis, energy model calibration and validation.
- The monitoring data processing was a very laborious process because of the very high amount of registered data and lack of automated tools to ease the work.
- The analysis of the hourly measured interior air temperature shows that throughout the year, the most frequent values are within the range 22 °C - 23°C. Only for 3% of the total number of hours, the interior air temperature falls below 22°C.
- The house faced overheating during summer, mainly due to the lack of shading systems for the windows. The cooling system was available for only a limited number of hours in August, as it was the preference of the building occupants.
- The primary energy consumption of the building, determined from measured data is of 106 kWh/m2y, which is below the passive house standard requirement (120 kWh/m2y) and also below the primary energy limitation for residential nearly zero-energy buildings in Romania (111 kWh/m2y).
- It can be said that the investigated building is a good practice example for achieving nearly zero-energy building standard in Romania, in terms of primary energy.
- The development of a building energy model for dynamic hourly simulations is a very laborious process due to the complexity and accuracy of the required input data but can lead to very accurate results.
- The statistical indices calculated from measured and simulated data are within the acceptance limits of calibration criteria. Accurate simulation results can be achieved if the input data of the building energy model follows the real operation conditions of the investigated building.
- The overall difference between measured and simulated is -1.107%, which means that the program slightly overestimated the energy consumption.
- The differences between measured and simulated monthly energy consumption are very small, and are mainly attributed to HVAC energy consumption.
- Over the entire year, the measured indoor air temperature are lower with an average value of 0.20°C than the simulated temperature.
- The heating energy consumption of the investigated building can be reduced with 8%, respectively 17%, if the heating temperature set point is reduced with 1°C (≈21°C), respectively 2°C (≈20°C).
- In order to reduce the gap between the designed and real energy consumption of a building, several scenarios for temperature set point should be investigated in the design phase of a building.
- Implementing shading systems can help reduce the interior air temperature during summer.
- It can be concluded that with shading devices available during the summer and night cooling, the interior air temperature can be maintained in acceptable limits without much use of an active cooling system.
- Cost optimal levels were investigated for the case study building: three building configurations achieved a plus energy balance, one achieved the net zero-energy balance and eleven solution achieved a primary energy consumption below the nZEB limit in Romania, and can be considered nearly zero energy buildings.
- The lowest global cost is achieved by the real building but with only a 2.8% increase of the global cost, the primary energy consumption of the real building can be reduced with 55%.
- The cost optimal analysis shows that the nearly zero energy building target can be achieved

also with a lower insulation level than passive house level, if it is combined with efficient technical system and/or renewable energy production.

- The scenarios that have the maximum number of photovoltaic panels lead to a surplus of energy.
- All the proposed energy efficiency packages lead to a significantly lower global cost and primary energy consumption compared to the reference building.
- The sensitivity analyses performed for different discount rates and energy price escalation rates, indicate that the scenarios that have very low energy consumption are not so sensitive to the future evolution of the prices or discount rates, which means that they can be considered safer solutions in front of the uncertainty that lies in the energy market evolution.
- Even though on a long time perspective, the highly energy efficient buildings proves to be more cost-effective than the reference buildings, the higher initial investment can be an impediment for most of the building owners.
- In case of the identified cost optimal solutions, the initial investment is higher with 19%, respectively 32% compared to the reference buildings. Higher differences occur along with the increase of photovoltaic systems or change of the heating/cooling system.
- The range of the investigated energy efficiency package is not very wide, as it include only two types of technical systems (excluding the reference building) and two envelope configurations.
- A more comprehensive study including different configurations might enlarge the cost-optimal range.

7.2. Personal contributions

- ➢ Study and synthesis of a large number of research papers and theses.
- ➢ Development of a strategy and procedure for processing a large amount of registered data by the monitoring system. Analysis and interpretation of the processed monitoring data.
- ➢ Generating customised input data based on monitoring for performing a tailored simulation of the energy performance of the case study building.
- ➢ Investigated the influence of different changes related to the building operation.
- ➢ Investigated the possibility of reducing the interior air temperature in the building
- ➢ Proposed and analysed 19 energy efficiency scenarios to be applied to the case study building and investigated each scenario in terms of primary energy consumption and global cost.
- ➢ Applied the cost-optimal methodology to the investigated energy efficiency scenarios.

7.3. Future work

The following future research activities are proposed:

1. Statistical processing and analysis of the monitoring data using the several years of recorded data.
2. Completing the monitoring system with some new measuring components that allows the breakdown of the energy consumption of the technical room. This will allow to better evaluate the performance of each component of the building technical systems.
3. Extending the cost-optimal studies by investigating other energy efficiency measures for both, thermal envelope and technical systems, in order to provide a wider range of solutions.
4. Extending the cost-optimal studies for all climate zones in Romania, considering the weather specific of each zone but also the national primary energy requirements in Romania for each climate zone.

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