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VALIDATION OF A TRNSYS MODEL FOR A COMPLEX HVAC SYSTEM INSTALLED IN A LOW-ENERGY BUILDING

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As the energy consumption in buildings sector is rapidly increasing, the need of concrete actions to be undertaken arises. An important measure with this respect is developing accurate models, used for analyzing strategies of energy intensity reduction. This paper focuses on developing a proper white-box mathematical model used to predict the energy behavior of a low-energy dwelling, built using the Passivhaus standard and placed in Bucharest, Romania. The model was developed using TRNSYS and was created from simple to complex, starting with the HVAC system (composed of an EAHX – earth to air heat exchanger, a MVHR – mechanical ventilation with heat recovery and an ER – electric resistance) and then integrating it within the building's framework. Moreover, each sub-model was first calibrated and validated using data gathered by the building's monitoring system. The model was then extended to analyze the indoor comfort and the energy consumption for heating the building. Finally, this complex model was used to simulate the behavior of the test house in other climatic regions from Romania to see if construction standard and the implemented HVAC system are still efficient. Thus, the model was run for six cities spread throughout the.

Keywords: TRNSYS simulation, model calibration and validation, low-energy building, energy efficient HVAC system, experimental data

1. Introduction

The building sector is a key factor to be addressed in the current worldwide energy context to fulfil long-term energy efficiency goals, as it represents approximately 40% of the final energy consumption and is constantly expanding [1,2]. Nevertheless, the residential sector has the biggest technical potential for increasing the energy efficiency, estimated by the European Commission at 30% [2]. In Romania, domestic energy consumption accounted for more than 35% of total final energy use in 2013 [3], as the share of residential buildings is up to 80 % [4]. A typical Romanian building's energy consumption is estimated at 250 kWh/m^2/year (less than 50 kWh/m^2/year is represented by electricity consumption), from which, up to 60% is used for heating the interior space [5,6]. Moreover, the average CO_2 emission index for the Romanian

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dwellings is estimated at 57 kg_{CO2}/m^2/year [5]. These facts are highlighted in the Romanian Energetic Strategy, which stipulates that the residential buildings have the highest energy efficiency potential, estimated between 35 and 50% [7], making the building sector a key factor in achieving the 2050 energetic and environmental goals.

For increasing the energy efficiency in the buildings sectors, the European Commission impose the implementation of nearly Zero Energy Buildings (nZEBs) as future cornerstone for new and retrofit buildings [1]. This is a general framework which must be transposed as national legislation by the Members, defined 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" [1]. The definition does not impose numerical limits for the construction to be categorized as nZEB but emphasizes the importance of using the sustainable energy sources to achieve the nearly zero energy label. Theoretical studies conducted for the Romanian climate conditions showed that by implementing major envelope improvement, minimizing its thermal bridges, integrating high efficient mechanical ventilation units and renewable energy sources, the total energy requirements for a building can be reduced by up to 95 % for single detached family house and up to 78 % for the office buildings, when compared to the reference models [4]. The best cost-efficiency performances were obtained when the improvements made over the building were the ones specified in the Passive House Standards (PHS) [8]. Furthermore, practical studies conducted so far showed that the passive houses succeed in maintaining optimal indoor comfort levels with minimum energy consumption and without using active heating and cooling systems when implemented in Bucharest or in the proximity, regardless of the building's functionality: residential [9,10,11] or tertiary [12,13,14].

To precisely analyse the behaviour of a certain building in a specific climate region, it's necessary to develop proper and accurate mathematical models. This approach was used by the Building Performance Institute Europe (BIPE) organization to analyse the possibility of implementing nZEB in different European regions [4,15,16]. In their reports, they used TRNSYS (TRaNsient SYstems Simulation) software to model and dynamically simulate different scenarios of multi-zones buildings and equipment used to decrease the energy consumption, given the analysed region's climate.

The aim of this paper is to calibrate and optimize a numerical model developed in TRNSYS for a low-energy residential building in Bucharest, Romania. The development of the model was realized in two stages: firstly, all components of the system were simulated in TRNSYS and the models were calibrated using experimental data; afterwards, all components were connected and simulated as a unitary system. The optimized model was further used to simulate the building behaviour in different climatic regions from Romania (colder and warmer). The purpose of this study was to establish if the used construction standard could be implemented throughout the country, without altering its energy performances and interior comfort levels.

2. Low energy building description

The research infrastructure used in this paper is a low-energy building placed in the University POLITEHNICA of Bucharest campus and equipped with a complete monitoring system. The low energy building was constructed in accordance with the Passivhaus standards and has been used for research purposes since 2013. The test building has a useful area of approximatively 140 m^2, and the rooms are distributed on two floors. The first floor is composed of a living-room, continued with an open space kitchen, a bathroom and a technical room, while on the second floor there are two bedrooms, two bathrooms, an office and a technical room. The house has a volume of almost 370 m^3, while the exterior envelope has a surface of approximatively 246 m^2, out of which, the fenestration represents an important part. For example, on the south façade, the total area of the windows sums 33% of the total.

The thermal envelope is composed of high quality and energy efficient materials, aiming to maximize the overall thermal resistances. Thus, the overall heat loss coefficients values range from 0.107 $W/m^2/K$ (roof) to 0.122 $W/m^2/K$ (exterior walls), complying with the Passivhaus standards, which imposes a maximal value of 0.15 $W/m^2/K$ for opaque elements [17]. The materials used for the thermal envelope provides also a huge thermal inertia and a large volume of thermal mass, minimizing the energy requirement for heating. The façade's finishing materials allows the natural air circulation, protecting the insulation against moisture. The building's envelope is completed by triple-pane high efficiency windows, characterised by low U-value (0.6 $W/m^2/K$) and high G-value (0.5) and an entrance door with the U-value coefficient of 0.78 $W/m^2/K$.

The indoor comfort is provided by a renewable energy sources-based HVAC system. The exterior air is sucked into the earth-to-air heat exchanger (EAHX) after being circulated through a sock-type air filter, to retain big impurities. The EAHX pre-heats (during winter) or cools (during summer) the inlet air, decreasing this way the thermal demand of the building. Previous studies indicated that the EAHX system is very efficient, even during transition periods, providing up to 9% of the heating energy required during the cold season [18].

The fresh air path continues with the heat recovery unit (MVHR – mechanical ventilation with heat recovery unit), where an important quantity of heat contained in the indoor stale air is transferred. This equipment is characterised by adjustable air flow rate and up to 93% heat recovery rate and covers a significant percentage of thermal energy requirements. During the analysed winter, the MVHR unit contributed with 34%, strengthening its applicability in energy efficient buildings [18]. The HVAC system is completed by a 2400 W electric resistance and three radiant heat panels, used only for peak periods. The electric resistance is driven by a temperature sensor, triggered based on some policies implemented through a Smart Building Controller – SBC [10].

As shown in Fig. 1 and previously detailed in [10, 18, 19], the house is equipped with a monitoring system, composed of wireless and wired sensors, a data logger and a data-storage system. The wired sensors provide information about the temperature variation through the fresh and stale air paths (T2 to T7), outdoor (T1) and indoor (T8) temperatures values. The wireless sensors are placed in each room and provide information about the temperature, relative humidity and luminosity levels. Additionally, the living-room is equipped with sensors measuring CO2 concentration and relative humidity levels. Solar radiation is measured by a pyranometer mounted on the roof and the electricity consumption of all consumers in the house is monitored by 7 energy meters.

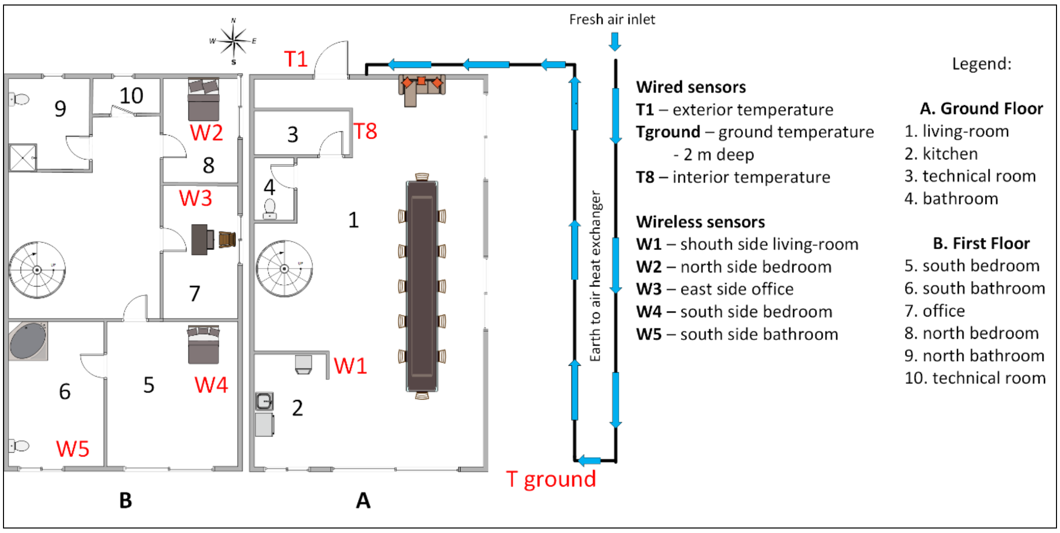

Fig. 1. Sensor distribution and HVAC system in the low-energy building

In Fig. 2 the path of the fresh and stale airflows through the MVHR unit is sketched. The fresh air path is symbolised with light blue colour while the stale air path with red colour. The wired sensors (from T2 – fresh air inlet to T7 – stale air outlet) positions are also highlighted. The sensors' positioning was chosen in a matter which allows the researchers to conduct complex studies regarding the thermal gains and losses through the ventilation system. This infrastructure was also the cornerstone for integrating an SBC solution, proposed for increasing the building's energy efficiency [10].

A significant part of the electricity consumed by the analysed building is provided by 13 PV panels, summing a total nominal installed power of 2.9 kW, coupled with an inverter having a nominal power of 3 kW. The system is grid connected, avoiding this way the necessity of an energy storage system.

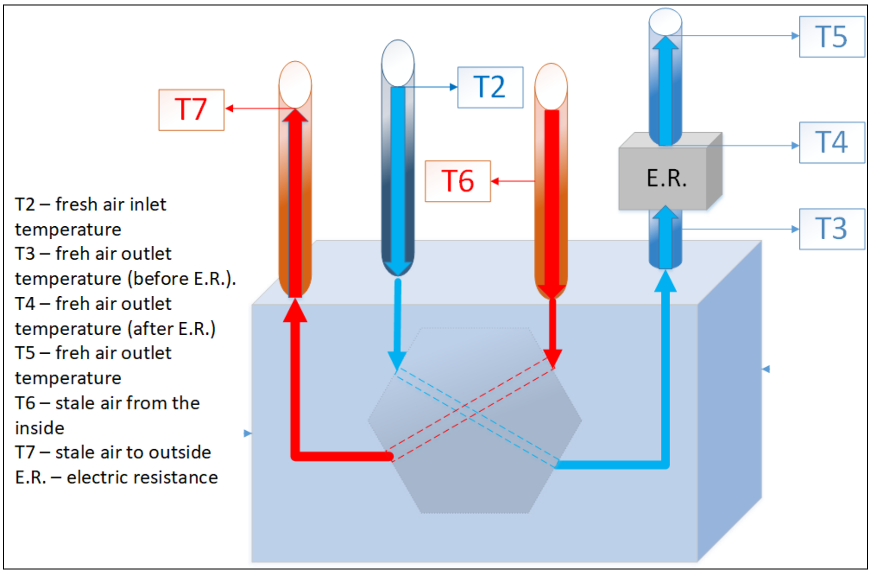

Fig. 2. Sensor distribution and air paths through the MVHR unit

3. Calibration procedure
3.1. EAHX system

Using the infrastructure described above, complex simulations were made to calibrate and validate the dynamic models realized using TRNSYS. For this, the data provided by the following sensors were used: T1, T2, Tground, T3, T4 and T8. The data used in this paper were harvested in 2014, summing 8760 hourly values.

Since the ground temperature plays and important role in the building's air conditioning system (the EAHX component), this parameter was calibrated using data harvested with Tground sensor. During the calibration process, different parameters were adjusted for the component Type 501 to overlap the two curves: model's results and harvested data. The most defining parameters for the soil component are: thermal conductivity (1.49 W/m/K), density (1800 kg/m^3), specific heat (1.34 kJ/kg/K) and depth of sensor's placement (2 m). Using these inputs, the results obtained over a year presented very good accuracy, and the two curves can be analysed in Fig. 3, where the real data was symbolized with red colour, while the modelled values are shown in red. The hourly relative error ranges between 0.001 and 23.5 %. Also, the absolute average error between the two temperatures was 0.47 °C over the whole year, indicating high accuracy of the model. The calibrated earth temperature model was further used to simulate the energetic behaviour of the analysed building in different Romanian cities.

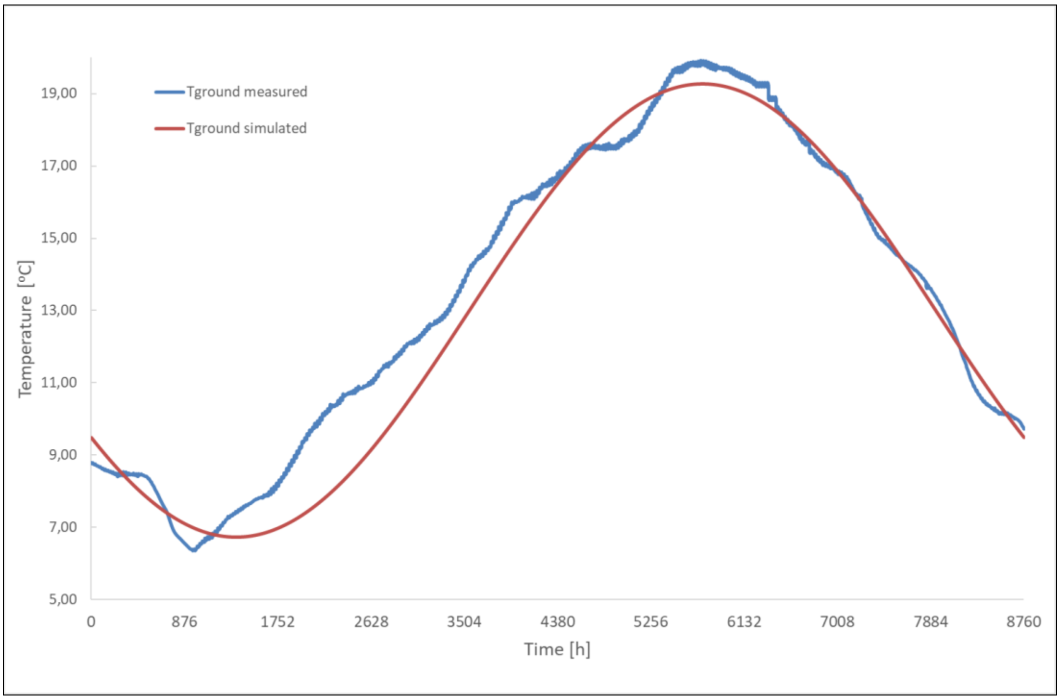

Fig. 3. Calibration of ground temperature

The simulations flow follows the fresh air path; thus, the next calibration was conducted for the Earth-to-Air Heat Exchanger equipment. In reality, the EAHX is composed of three sections. Each of the three parts is influenced by different parameters, as the surrounding environment is distinct: the first section is directly influenced by the outdoor weather conditions, as it is buried on the eastern part of the building where no shading elements are present. The second and third parts are shorter in length and are positioned under and inside the building, respectively. Thus, the influencing temperature does not vary as much as the ambient one.

Therefore, during the calibration of the model, the same three parts were considered. The first component has a length of 38 meters and for its simulation Type 556 was used, which portrays a pipe buried at a certain depth in the ground. This type considers the following simulation parameters: the inside diameter (0.1844 m), pipe length (38 m), loss coefficient of the air side (4 $W/m^2/K$), fluid density (1.25 kg/m^3), fluid specific heat (1.011 kJ/kg/K). The temperature of inlet air was considered the outdoor temperature (measured by the sensor T1) and for its flowrate the measured value of 0.2 m^3/h was imposed. The outlet temperature and flow rate obtained for the first section are the inputs for the next sections of the EAHX. For the other two sections Type 31 was considered. This represents a simple pipe with user defined environmental temperature.

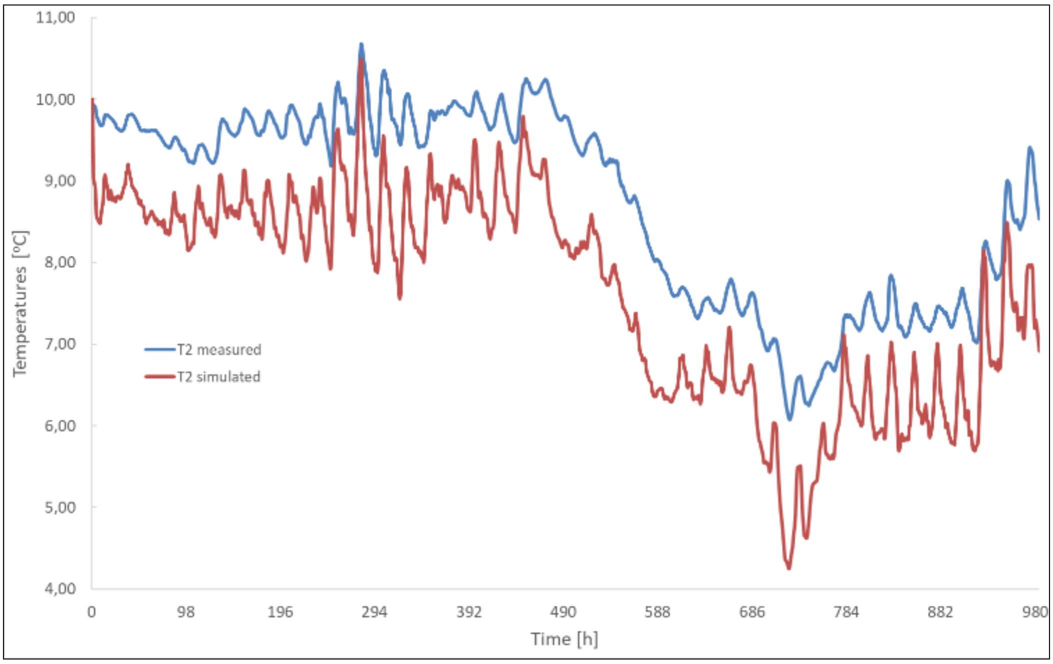

Fig. 4. Outlet air temperature for EAHX calibration (1 January – 10 February)

For the calibration process, three characteristic periods, which include all seasons, were considered. The first one, starting from the 1st of January until 10th of February, is presented in Fig. 5 and represents the behaviour of the system during the coldest period. As it can be observed, the curves allure follows the same trend, with a larger amplitude for the measured values. This is since, during the simulation, the two Types used for the EAHX do not require the solar radiation as input. This leads to lower values for the results of the simulations.

The other analysed periods are shown in Figs. 5 and 6, which show the thermal behaviour of the equipment during spring, summer and autumn. The first period between 26th of March and 9th of June presented a maximum relative error of 18.8%. The second interval was considered between 13th of August – 23rd of September, having the relative error ranging up to 13%.

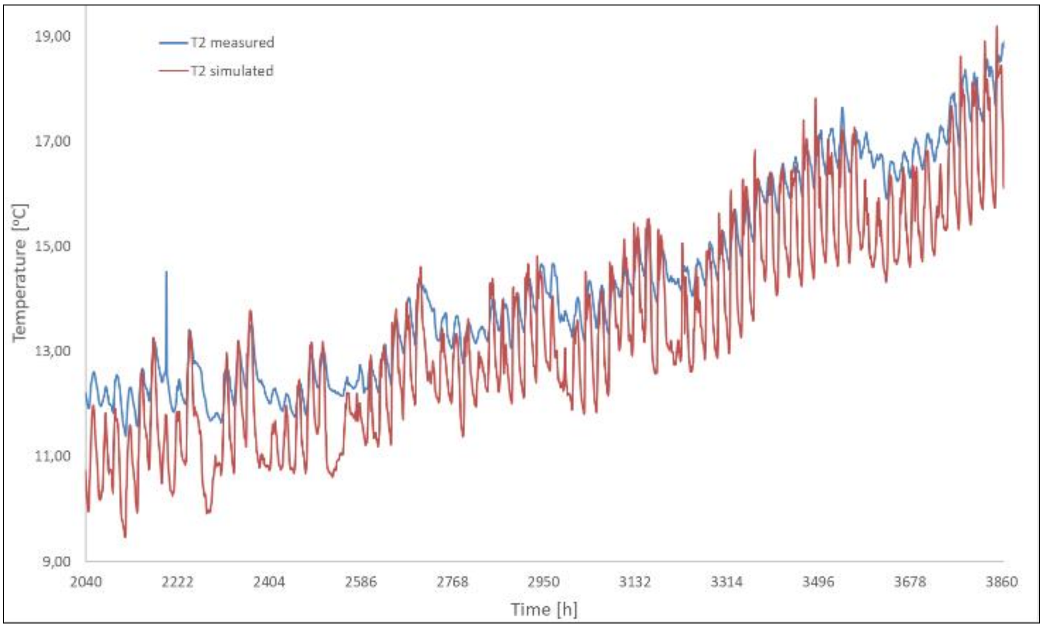

Fig. 5. Outlet air temperature for EAHX calibration (26 March – 9 June)

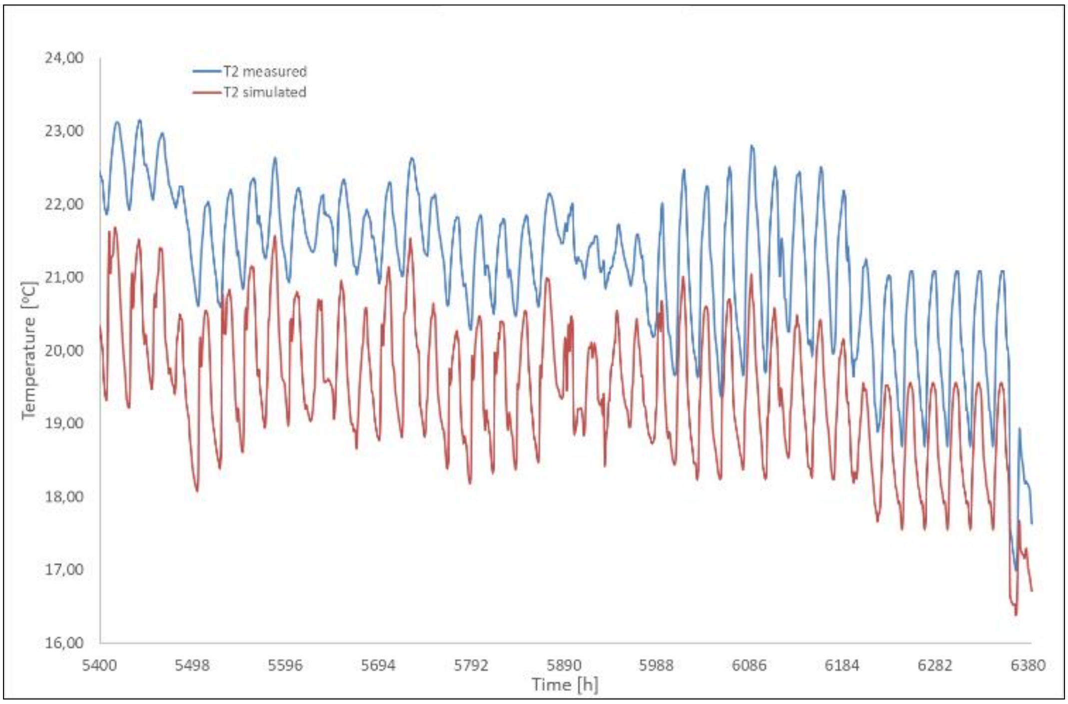

Fig. 6. Outlet air temperature for EAHX calibration (13 August – 23 September)

3.2. MVHR system

The next step in the calibration process was to simulate the thermal gain of fresh air through the MVHR unit. For this model, the TRNSYS Type 667b was used and its parameters were modified to meet the measured values. The fresh air inlet and stale air inlet temperatures together with their flow rates were used as input parameters for this module. The inlet fresh air temperature at MVHR unit inlet is the same as outlet air temperature from the EAHX system (T2). Since the difference between values measured by stale air temperature sensor at MVHR inlet (T6 – Fig. 3) and indoor air temperature sensor (T8) are negligible, we used the latter ones. The results of the simulation – fresh air outlet – were compared with the data harvested from the T3 sensor, as illustrated in Figs. 7, 8 and 9. The heat recovery unit was calibrated by modifying the following parameters: rated power (70 W), exhaust/fresh air pressure (1 atm), sensible effectiveness (0.9) and latent effectiveness (0.05). The air mass flow rate was considered the same as the one through the EAHX system, as no air pressure losses occur.

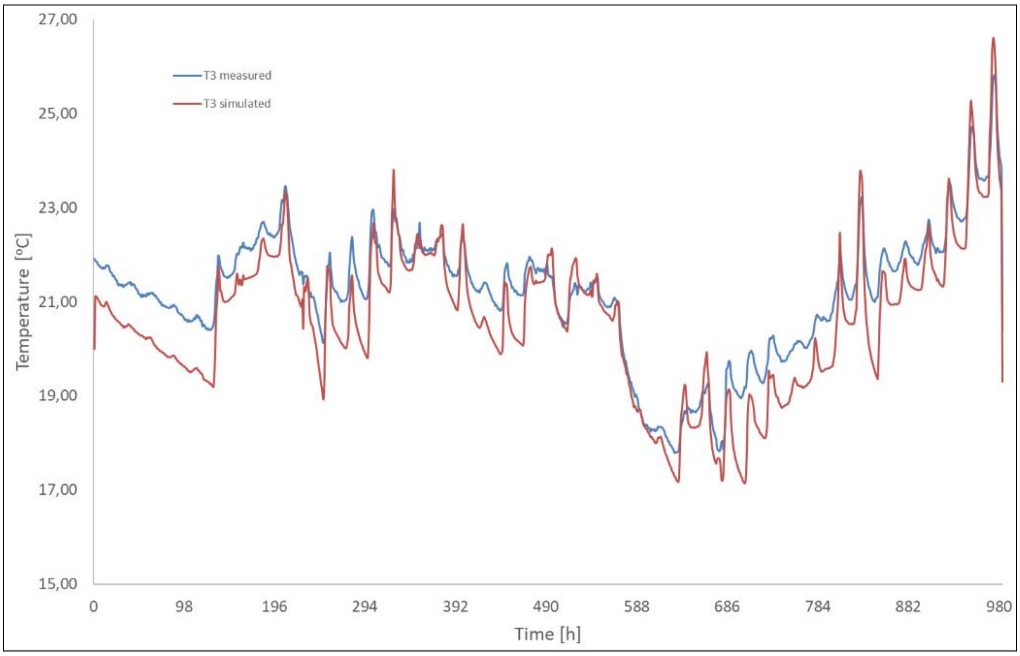

Fig. 7. Outlet fresh air temperature for MVHR calibration (1 January – 10 February)

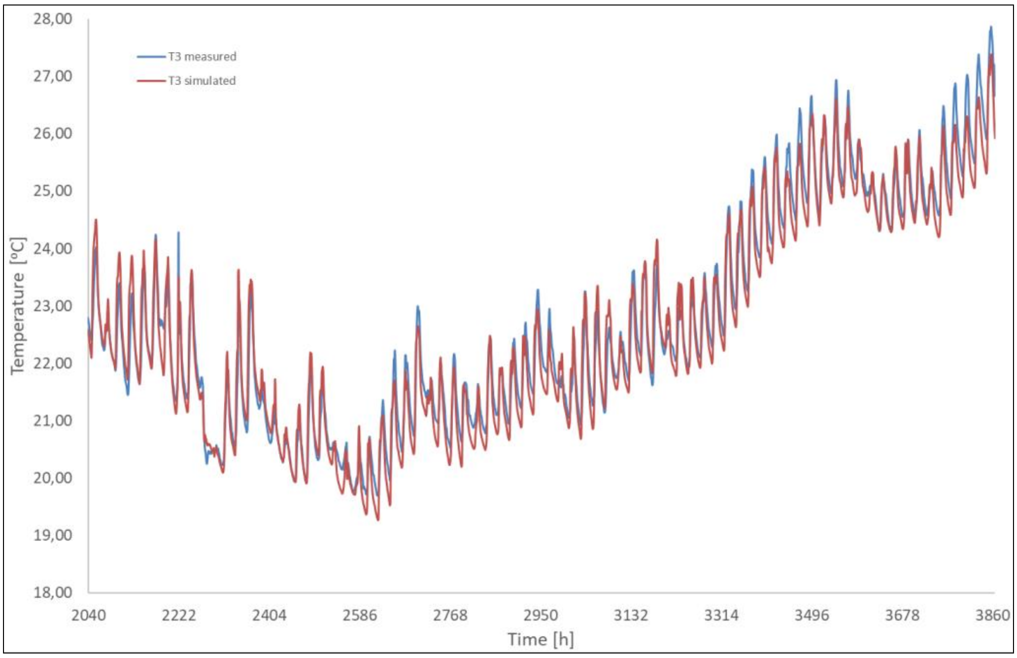

Fig. 8. Outlet fresh air temperature for MVHR calibration (26 March – 9 June)

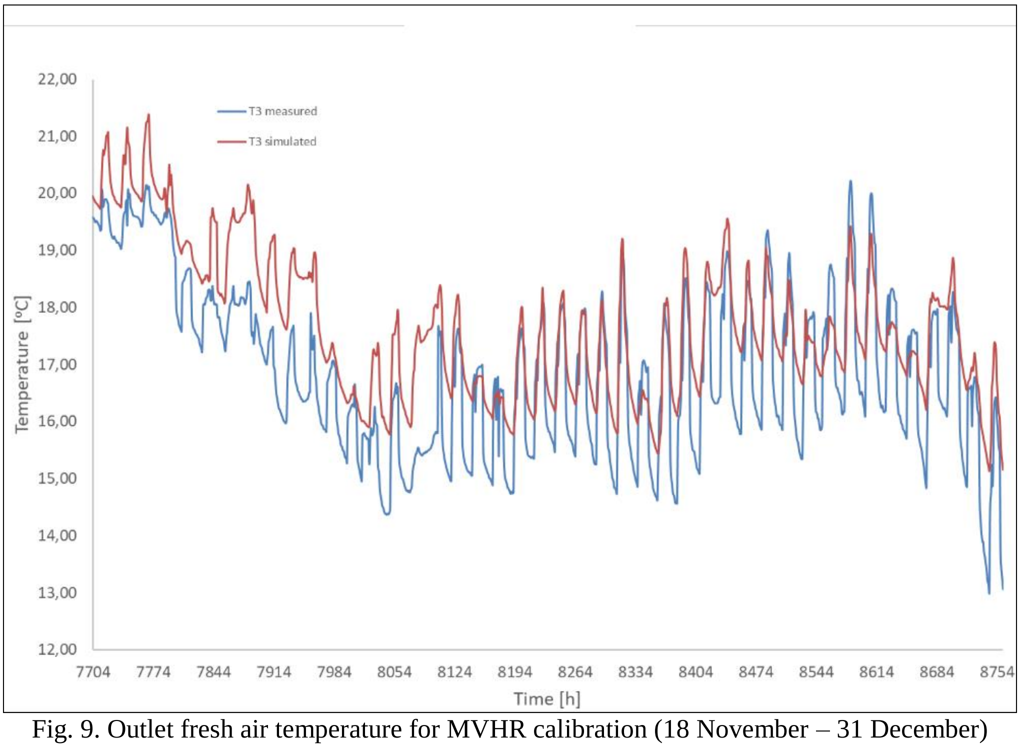

Fig. 9. Outlet fresh air temperature for MVHR calibration (18 November – 31 December)

For this calibration procedure, the following periods were chosen: 1st of January – 10th of February; 26th of March – 9th of June; and 18th November – 31st December. These intervals were analysed since the MVHR unit can be bypassed when the interior comfort temperature can be reached directly from the EAHX system. This usually occurs during hot season when no extra heat is required. Thus, the measured vales within that specific period can be misleading for the calibration of this component, implying increased errors. Only considering the proposed calibration period, the maximum recorded relative error was16.3%, occurring during the last interval.

4. Overall building's simulation

Following the calibration procedure, we simulated the energy behaviour of the low-energy building described in Section 3. The thermal properties of the building's envelope, its dimensions, electronic devices and operating schedule were all inputs in Type56 (TRNBuild) module. For creating the geometry, the Google SketchUp software was used, and the virtual model of the building is shown in Fig. 10.

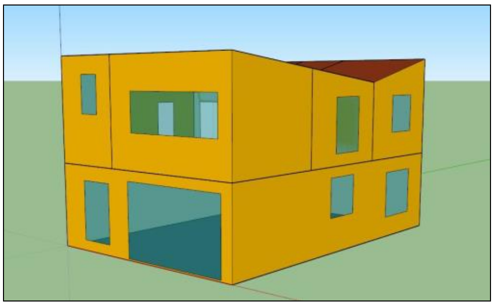

Fig. 10. South-east view of the low-energy building sketch.

The thermal properties of the materials used as inputs for the analysed building can be found in previous published papers [9, 10]. Regarding the internal heat gains for the living room, a density of 0.025 persons/m^2 conducting light work and 3 PCs of 140W each were considered during working periods (8 hours/day, 5 day/week).

Being placed in Bucharest, four seasons climate area, the building requires both heating and cooling. Taking into consideration the large amplitude of the environmental temperature between summer and winter, it rose the necessity of integrating a bypass on the fresh air path. Thus, during cooling periods, the fresh air delivered to the house comes directly from the EAHX system. On the other hand, during cold periods, the interior comfort is reached due to the MVHR and ER system. For modelling this infrastructure, the flow path was conditioned by an outdoor temperature level, integrated using a mathematical equation. In this respect, if the outside air temperature is below 16 °C, the heating system is turned on, otherwise the MVHR and ER system is bypassed.

The TRNSYS diagram of the simulation is presented in Fig. 11. This was used for calibrating, validating and simulating both the complete HVAC system and the low energy building. The type used in the simulation of the earth's temperature is represented by *Tground* component which will be further used in this study as input temperature for the EAHX system. The latter is depicted using three components, as previously described: *EAHX–1* (outdoor), *EAHX–2* (under the building) and *EAHX–3* (indoor). The pre-treated air path continues with the bypass controller, which decides which path to use: *ventilation_no_bypass* (heating period) and *ventilation_bypass* (cooling period). The red line shows the flow passing through the MVHR and ER system, while the blue line depicts the bypassed flow. Moreover, the electric resistance is controlled by an interior thermostat set at 21 °C and a predefined schedule (working days), reducing in this way the overall energy consumption for heating. Finally, the two air flow streams are joined using Type11h, providing the conditioned air to the simulated building (*Building*). The picture is completed by weather and plotting components.

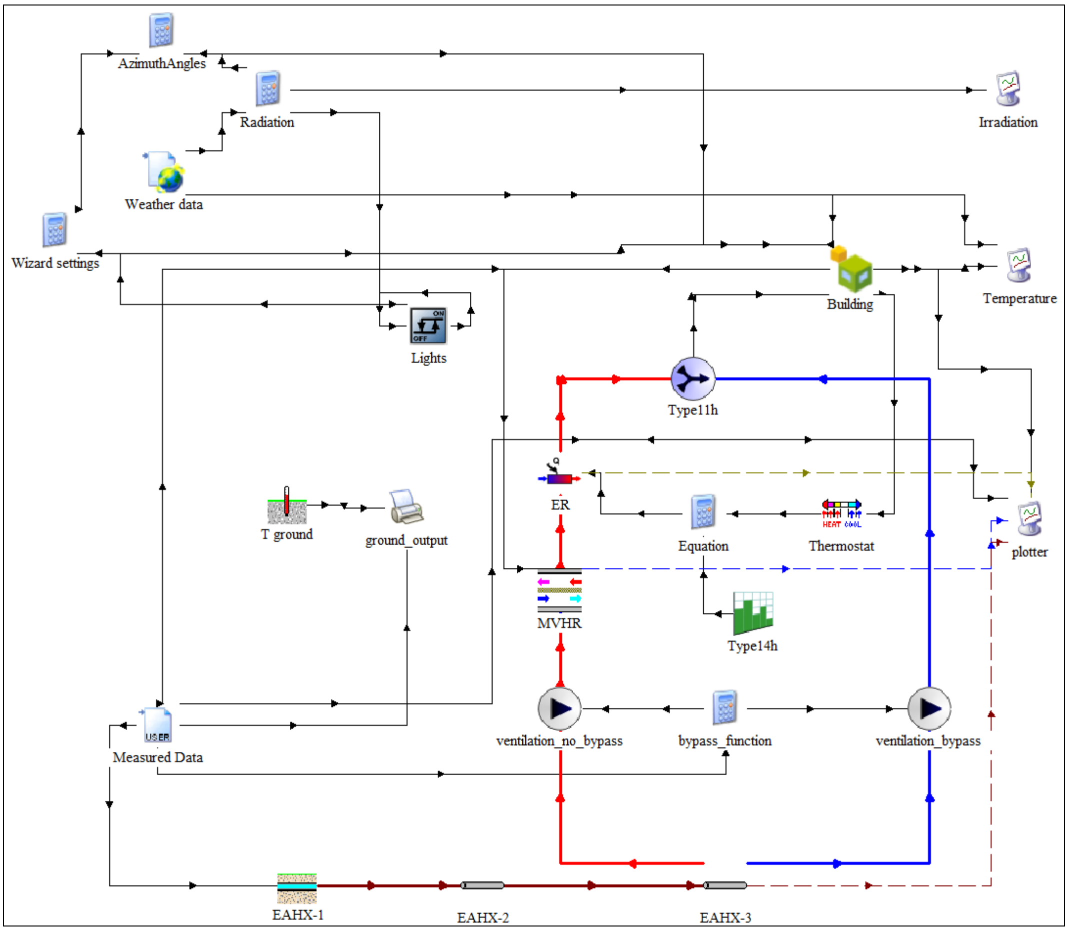

Fig. 11. Overall TRNSYS simulation diagram

By using this, the indoor comfort temperature was simulated first using measured data. To be able to expand the utilization of the implemented model, a second simulation was conducted using the environmental data provided by

TRNSYS file for Bucharest (Meteonorm). The results can be analysed in Fig. 13, where both simulations were compared with the measured values. The considered indoor air temperature was the one measured in the living-room by sensor T8, as the temperature differences between the other zones was negligible.

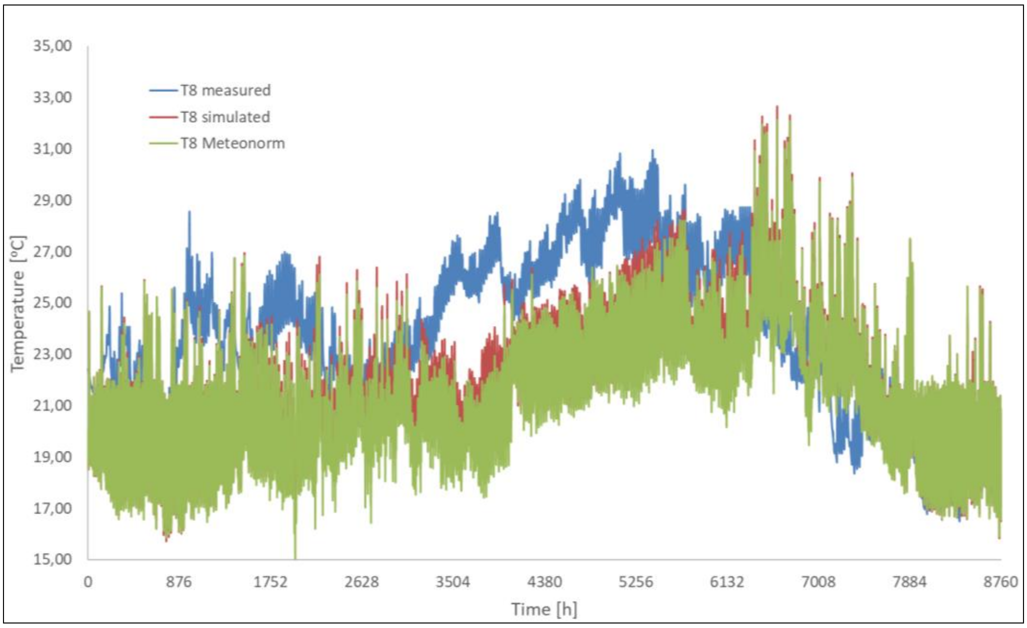

Fig. 12. Indoor comfort temperature comparison

The TRNSYS models require the solar radiation data for each surface. As the measured data is harvested only on the rooftop (15° angle), the model was provided with the solar radiation from the Meteonorm file, thus increasing the difference between the models' results and measured data. This difference is higher during summer periods, mainly because of the sun's position on the skyline and large fenestration surface on the south façade. The latter in conjunction with the fact that there were no shading elements installed at the time, decreased the indoor thermal comfort levels during summer, when the temperature surpassed 26℃ for 26% of the time during a year. Also, given the fact that the building is occupied only during daytime, the temperature can reach lower values during the night-time in heating periods. For the simulated values of the living-room temperature, for both models, the percentage of time when the interior comfort was not met, was less than 10%, decreasing the liability of the mathematical formulation.

The next simulation was conducted to predict the energy consumption of active heating system (ER). It can be observed that during the cooling period, the consumption is 0, as the electrical resistance is bypassed and set offline. Therefore, the annual energy consumption was 964 kWh for the model using measured data as inputs and 1020 kWh for the Meteonorm model, thus the errors are in acceptable ranges.

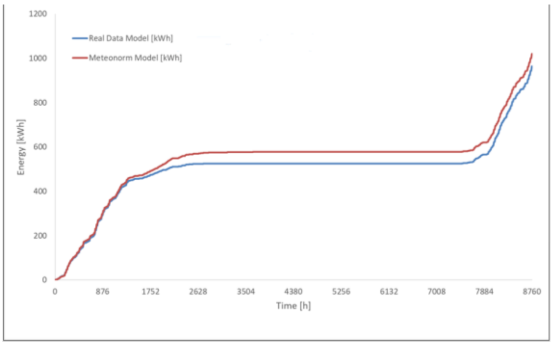

Fig. 13. Comparison of energy consumption for heating

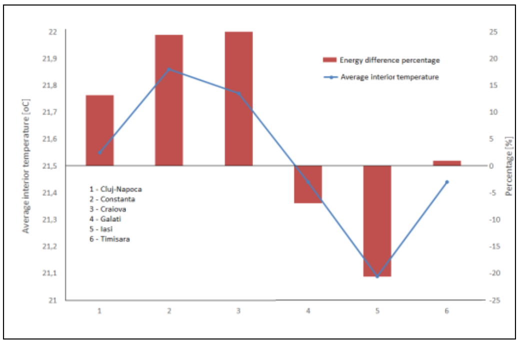

Fig. 14. Interior comfort and energy consumption comparison for 6 different towns

The same mathematical model was further used to analyse different cities from Romania, as the country is characterized by all landforms. Also, the ambient temperature differs significant from North to West and South. In this paper, we simulated the building and the HVAC component for the following cities: Cluj-Napoca, Constanța, Craiova, Iași, Galați and Timișoara, as they were considered the most representative for each part of the country.

The climate file for each city was used within the calibrated HVAC model to predict the ER energy consumption for the same building (same construction materials and same surfaces) in the respective areas. This type of simulation is useful to analyse the behaviour of a certain construction in different climatic regions to optimize the energy consumption and indoor comfort levels. The consumption results, compared with the base case of Bucharest, are shown in Fig. 14. As suggested by the climatic data, the smallest energy consumption for heating was found for Constanţa, Craiova and Cluj-Napoca cities, while the biggest values were recorded for Iași, mainly because it is in a mountainous region and the requirements for heating are higher than in the other cities. Moreover, for all simulations, the average indoor air temperature was found to be within comfort limits with small variations for the analysed cities. These facts show that the construction will perform efficient even if placed in other regions in Romania, thus the nZEB criteria will be met as well.

5. Conclusions

Given the rising need to build accurate models to analyse the impact of different strategies over the overall buildings' energy intensity, this Paper present a detailed and accurate white box model implemented using TRNSYS software.

The model is applied to a low-energy building placed in Bucharest, Romania, and is equipped with monitoring systems which give information about the performances of the HVAC system, composed of EAHX and MVHR subsystems. The mathematical model was developed gradually, from simple to complex and gives the researchers the information about the facility's behaviour when placed in different climatic areas. This was possible given the modularity character of TRNSYS, allowing the user to develop simple models and concatenate them to form a complex analysis.

Firstly, the calibration procedure was undertaken. Each HVAC sub-system was analysed separately, without neglecting the interconnection between them, thus assuring that the ground temperature is simulated accurately. The calibration of this parameter was realized by adjusting the features of Type 501 component and comparing the results with data harvested from underground sensor. The hourly relative errors were less than 23.5%, showing fair accuracy over the analysed year. The calibrated Type 501 was then connected with the EAHX components (Types 556 and 31 in TRNSYS) and the outlet temperature's predicted values presented errors up to 18.8% when compared with measured values. The MVHR subsystem was calibrated modifying the parameters of Type 667b in TRNSYS to match the measured data. The calibration procedure showed fair results, as the error did not exceed 16.3%, regardless the considered period.

The calibrated HVAC system was further used to simulate energy performances of the studied low-energy building. The thermal properties of the envelope and the dimensions were used within TRNBuild Type and the geometry was created using Google SketchUP. The HVAC system was completed at this stage of development by integrating the electric resistance, controlled by an indoor thermostat set at 21℃ and a predefined occupancy schedule. A bypass was installed to control the MVHR subsystem and its functioning is based on an imposed exterior temperature threshold (16 ℃). Using this configuration, both indoor comfort temperature and energy consumption were comparable with measured values. Moreover, the comparison between the energy consumption for heating simulated using measured and Meteonorm data, emphasizes the accuracy of the model, as the difference between the two results was only 56 kWh over the entire year analysed. The study was extended, and the calibrated building was virtually placed in other 6 different regions from Romania, chosen based on their different climate. In each region, the nZEB criteria was met, emphasizing the efficiency potential of the Passivhaus construction standard and HVAC systems in achieving the desired energy reduction.

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